TECHNICAL REPORT

FULL PRESSURE SUIT HEAT BALANCE STUDIES

LS-140 February 1965

Prepared for

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Prepared under Contract No. NAS 9-2886 by
AiResearch Manufacturing Company
Los Angeles, California

GARRETT AIRESEARCH MANUFACTURING DIVISION
Los Angeles, California

Rpt - 33117

TECHNICAL REPORT

FULL PRESSURE SUIT HEAT BALANCE STUDIES

LS-140 February 1965

Prepared by

E. C. Wortz, Ph.D.
R. A. Diaz
D. K. Edwards, B.S.
L. E. Browne, B.S.
E. J. Prescott, Ph.D.
G. L. Scherer, M.D.
F. H. Green, B.A.

Prepared for

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Prepared under Contract No. NAS 9-2886 by
AiResearch Manufacturing Company
Los Angeles, California

GARRETT AIRESEARCH MANUFACTURING DIVISION
Los Angeles, California

ERRATA

February 19, 1965

Technical Report LS-140

FULL PRESSURE SUIT
HEAT BALANCE STUDIES

Prepared by E. C. Wortz, et al.

AiResearch Manufacturing Company
Los Angeles, California

February 1965

(Prepared for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas under Contract No. NAS9-2886)

1. Page 2. In paragraph 1, line 17, change "(STP)" to "(ATP)."

2. Page 9. In paragraph 4, line 6, change "0.010 in." to "0.001 in."

3. Page 35. In paragraph 2, line 3, the word "this" should precede "last data point."

4. Page 197. In paragraph 10, line 1 and paragraph 11, line 1, the name "Dubois" should be "DuBois."

5. Page 198. In paragraph 1, line 1, the names listed should be changed to reflect the correct spelling, as follows: "Aikas, E.; Karvonen, M. J.; Piironen, P.; and Ruosteenoga, R."

FOREWORD

This report was prepared in the Department of Life Sciences, AiResearch Manufacturing Company, Los Angeles, California by:

E. C. Wortz, Ph.D.

R. A. Diaz

D. K. Edwards, B.S.

L. E. Browne, B.S.

E. J. Prescott, Ph.D.

G. L. Scherer, M.D.

F. H. Green, B.A.

The technical assistance of N. J. Belton, W. S. Schreck, R. Godson, E. Maltby, S. L'Hommedieu, and V. G. Gettemy, is gratefully acknowledged.

CONTENTS

CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

FULL PRESSURE SUIT HEAT BALANCE STUDIES

SUMMARY

This report describes experiments conducted to establish a thermal balance between heat removal and metabolic rate in the pressurized Gemini G2-C full pressure suit at sea level and at 32,500 ft. The pressure suit ventilation gas inlet conditions employed in this experiment were dew-point temperature of 33°F, flow rate of 17.1 ft^3/min with the suit pressurized to 3.7 psig over cabin ambient, and dry-bulb temperatures of 76°F at sea level and 50°F at altitude.

Data are reported for ten subjects exercising at 1.4 and 2.0 mph on a level treadmill. Conclusions are drawn concerning metabolic rates, heat storage, and the adequacy of sea level simulation.

SECTION I

INTRODUCTION

A number of experiments have been conducted to answer some of the problems of thermal balance in pressurized suits. Typical of these experiments are those of Nelson (1962), Lang (1963), Wortz, et al. (1963), Albright, et al. (1964), and Harrington, Edwards, and Wortz (1964).* In general these experiments have demonstrated that, for a given rate of suit ventilation, the rate of heat removal decreases as barometric pressure is reduced from sea-level pressure. In addition, the rate of heat storage is increased. The maximum rate of heat removal by ventilation alone was reported by Albright, et al. in Reference 4 (1964) as 1441 Btu per hr for a subject exercising at 1.5 Kp on a bicycle ergometer (metabolic rate of 1655 Btu per hr). This experiment was conducted with the subjects wearing an unpressurized "Apollo prototype" suit at a simulated altitude of 35,000 ft, with a suit inlet flow rate of 4.1 cfm (STP), a pressure of 3.73 psia, and a saturation temperature of 43°F. On the other hand, Wortz, et al. (Reference 6, 1964), found a maximum heat removal of 1425 Btu per hr for subjects exercising on a treadmill at metabolic rates of approximately 1750 Btu per hr; the subjects were wearing suits pressurized to 3.5 psig (7.1 psia), and the ventilation gas flow rate was 26.0 cfm (STP) and saturated at 45°F.

These experiments have been hampered, as have most studies of thermal balance in pressure suits, by procedural difficulties, such as the utilization of a small number of subjects or attempting to determine metabolic rates by measuring the production of carbon dioxide, etc.

The objectives of the experiment described by this report were to investigate the effects of various metabolic rates on the thermal processes in the Gemini G2-C full-pressure suit at two barometric pressures (14.7 and 3.9 psia) with the suit pressurized to 3.7 psig. The independent variables in this experiment were: the subjects, absolute pressure, suit inlet dry-bulb temperature; and work rate. The manipulations of these parameters, the dependent variables, results of the experiments, a discussion of the results, and conclusions are described in the following sections of this report.

---

* References 1 through 5

SECTION 2

APPARATUS

ALTITUDE CHAMBER

The heat balance studies were conducted in the AiResearch R&D laboratory, in a low-pressure altitude chamber designed specifically for human physiological research. The main chamber has an internal volume of 750 cu ft and is equipped with a 250-cu-ft airlock, with windows for visual observation of test subjects at simulated altitudes. Communications with the chamber occupants were maintained throughout each test by means of an aircraft-type low impedance intercom system. The chamber and airlock were also equipped with an oxygen supply for the test observer's mask, and with an emergency oxygen supply consisting of pressurized "walk-around" bottles that could be attached to the masks. The mechanism used to induce the various desired metabolic loads on the test subjects was a variable-speed level treadmill, so situated in the chamber that a minimum length of ducting was required in the suit ventilation circuit. Figure 1 shows the interior of the main chamber as it was equipped and instrumented for this experiment. The internal radiant and ambient temperatures of the main altitude chamber were maintained at 96°F by ordinary electric blankets wrapped around the outside of the chamber. Two of the blankets were used inside to form a door-like partition in the main chamber to prevent the formation of thermal gradients and convection eddies. Thermocouples were located both on the internal wall surface of the main chamber and in the interior air to measure radiant and ambient temperatures. Figure 2 shows the location of these thermocouples.

ENVIRONMENTAL CONTROL SYSTEM

The altitude chamber was equipped with an environmental control system (ECS) prepared specifically for this experiment. This system was designed to condition a desired mass of gas to specified dry-bulb temperatures and water vapor pressures within narrow limits, over a wide range of flows, temperature, and relative humidity. A schematic drawing of the ECS is shown in Figure 3. The conditioned suit-ventilation gas was monitored extensively and held within ±2.0°F dry-bulb and ±2.0°F dew-point temperatures. To obtain these conditions, cryogenic oxygen was vaporized and ducted through a pressure regulator to a saturation chamber for aqueous saturation at a high temperature. The supersaturated gas then passed through a primary gas-to-liquid heat exchanger, where it was cooled and a portion of the water vapor condensed and trapped, so that the emerging gas was at the desired saturation temperature (measured as a dew-point temperature). From the primary heat exchanger, the gas passed through a reheater to attain the desired dry-bulb temperature; from this point the gas was ducted through the altitude chamber bulkhead to the secondary gas-to-liquid heat exchanger, which was used for final adjustment of the suit inlet dew-point temperature. From the secondary heat exchanger, the gas passed through a temperature-controlled laminar flow element, which was used to determine the suit inlet ventilation rate. From the laminar flow element, the gas was ducted through a temperature-controlled flexible convoluted

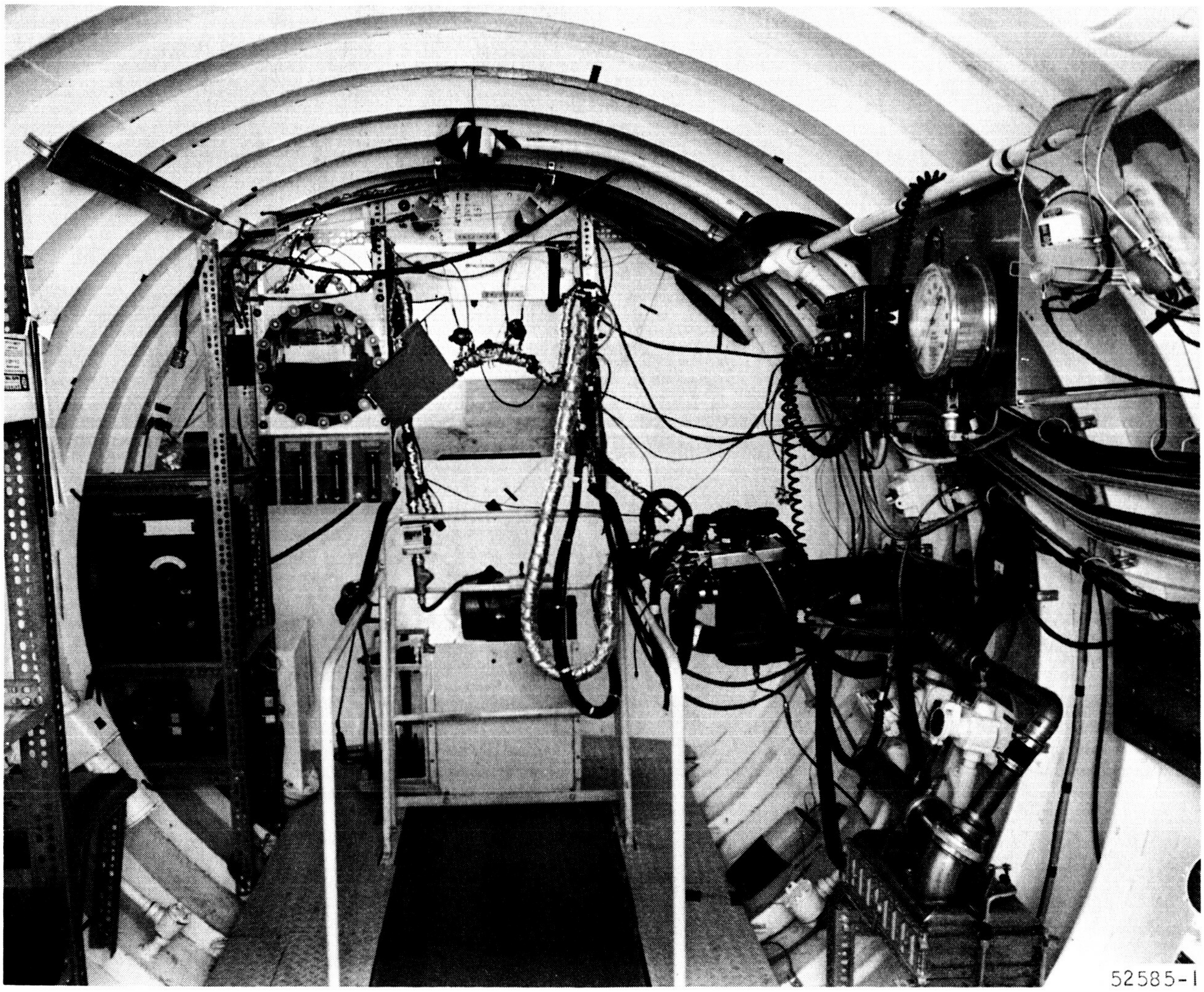


Figure 1. Main Altitude Chamber

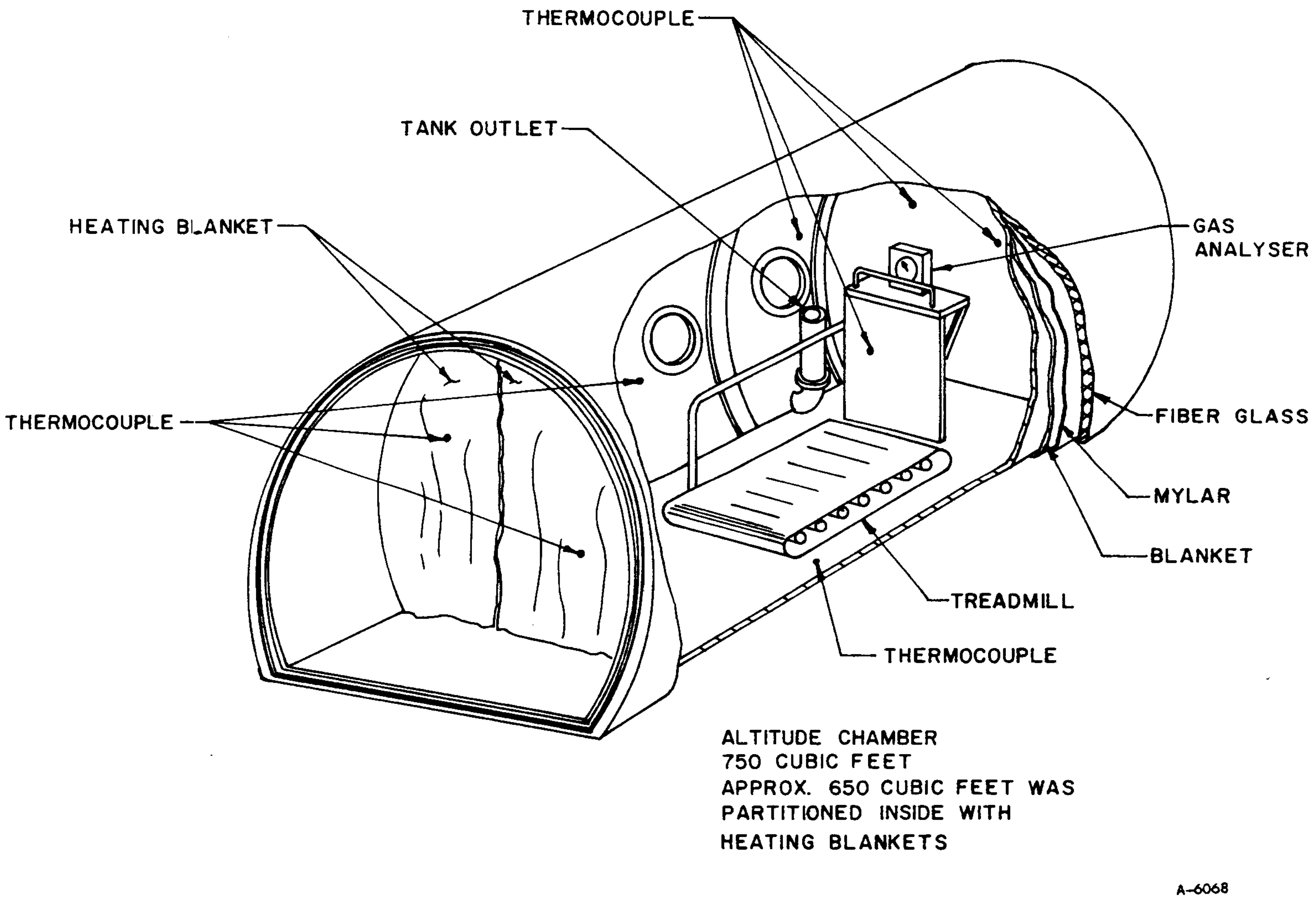


Figure 2. Sectioned View of AiResearch Altitude Chamber Facility Showing Thermocouple Locations and Heating Blankets

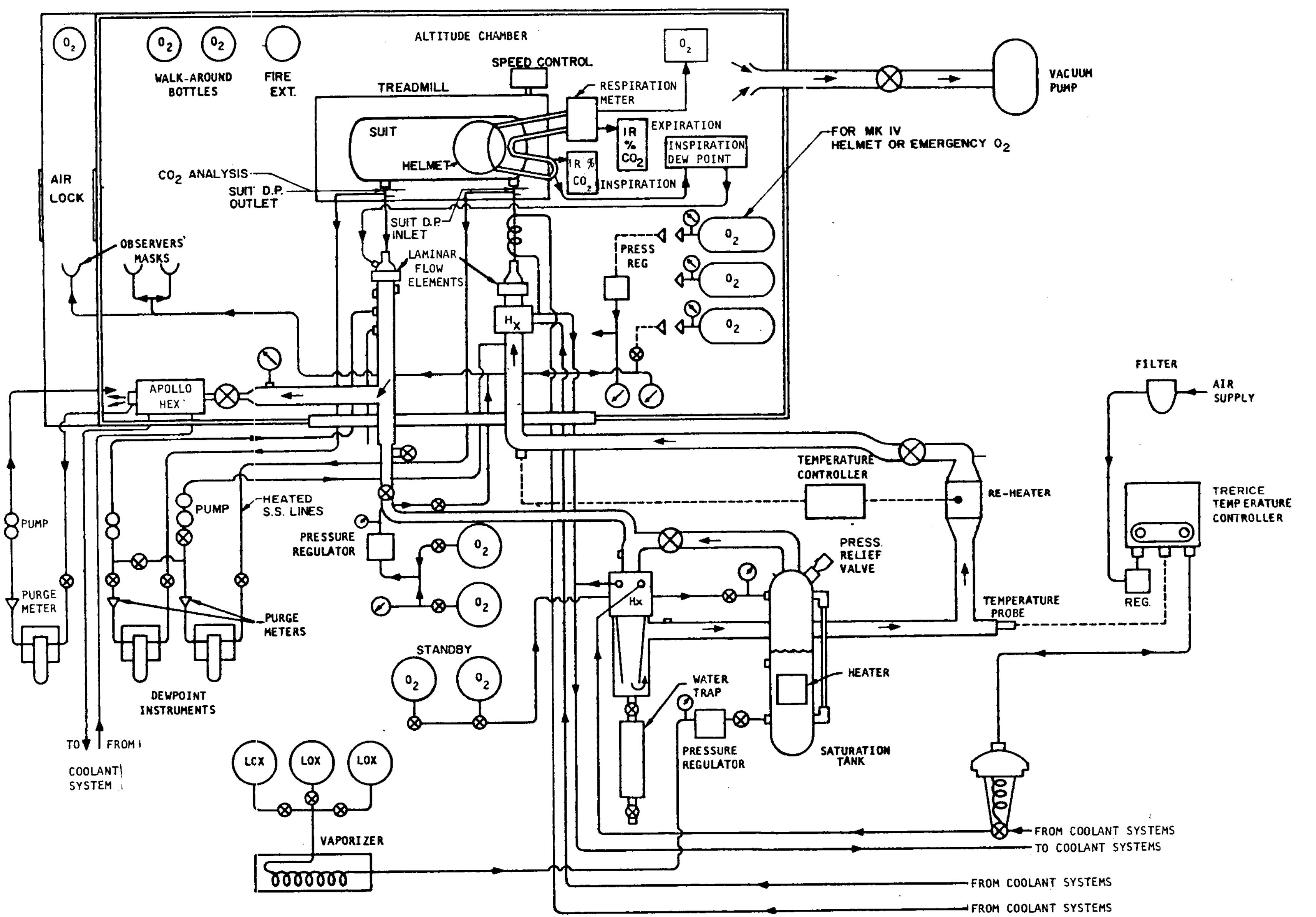


Figure 3. Schematic Diagram; AiResearch Altitude Chamber Environmental Control System and Instrumentation

B-581-A

hose directly into the suit inlet port. The suit outlet gas was ducted from the suit outlet port through a flexible convoluted hose to the suit-outlet laminar flow element. From the laminar flow element, the gas was ducted through a gate-type valve, which was used to establish the desired suit-to-cabin differential pressure. From this valve, the gas passed through an Apollo suit circuit gas-to-liquid heat exchanger (P/N 81300), and was then exhausted into the altitude chamber. The Apollo heat exchanger was used to adjust the suit outlet dew-point temperature to equal the suit inlet dew-point temperature. The water vapor that was condensed and trapped at this point was collected and subsequently measured. To facilitate thermal control, the system ducting was completely insulated with Armstrong Armaflex 22. The suit-inlet flexible hose was wrapped with a liquid coolant tube and with a high-resistance heating tape, with evenly spaced intervals between the coolant tube and heating tape. The coolant tube and heating tape were used to maintain a precise suit-inlet dry-bulb temperature and to prevent condensation of water vapor within the hose. Figure 4 shows the coolant distribution schematic.

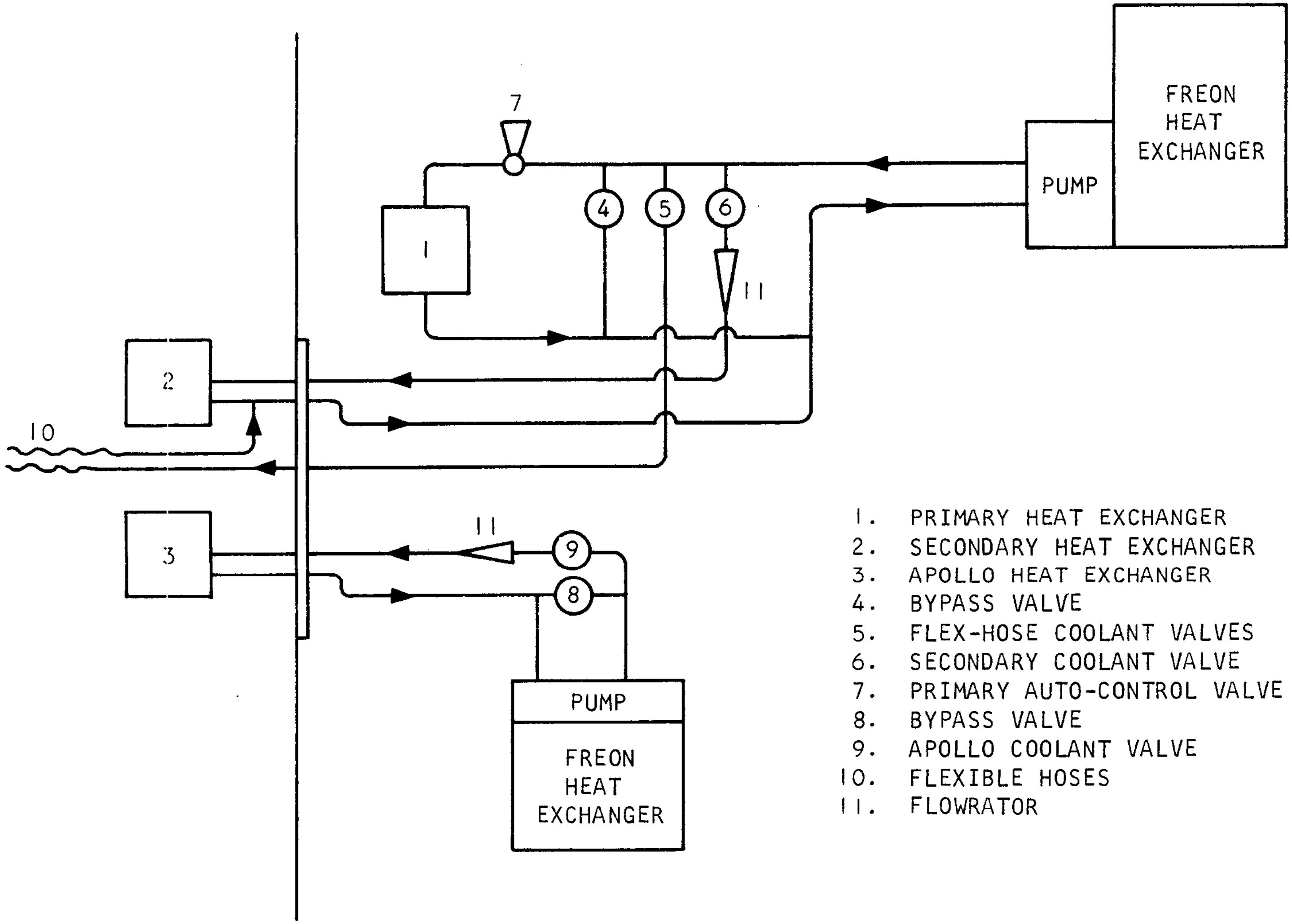
SYSTEM INSTRUMENTATION

Dry-Bulb Temperature Measurement

The dry-bulb temperatures of the suit-inlet and suit-outlet ventilation gas were measured independently at the suit inlet and outlet quick-disconnect fittings. A copper-constantan thermocouple was situated at each of these fittings to measure the exact temperature of the gas entering and leaving the suit. The thermocouples were connected directly to a Honeywell-Brown strip-chart recorder. All other system and instrumentation temperatures were measured with copper-constantan thermocouples that were connected to one of two Honeywell-Brown strip-chart recorders.

Dew-Point Measurement

A series of four dew-point instruments were used independently to measure dew-point temperatures at the following locations: suit inlet, suit outlet, Apollo heat exchanger outlet, expiration dew point, and inspiration dew point. The dew-point sampling technique consisted of the following: (1) a small portion of the gas was picked up at the sample point and ducted through heated flexible and heated stainless-steel lines to its appropriate dew-point instrument; (2) the gas sample entered the heated dew-point cell and passed over a heated glass-chromium mirror mounted on a copper base, which extended into a methanol and dry-ice heat sink; (3) a controlled reduction in the amount of electrical current passing through the heating element of the mirror-copper base reduced the surface temperature of the mirror, causing dew to form on it at the water vapor dew-point temperature; (4) light from an incandescent source within the sample cell was reflected away from the microscope by the mirror until the angle of incidence was changed by dew formation on the mirror; (5) the light reflection then was detected by visual observation through a four-power microscope mounted on the sample cell. The mirror surface temperature was sensed by a copper-constantan thermocouple embedded 0.001 in. beneath the surface of the mirror. The thermocouple leads were connected to a water- and ice-bath reference junction; from this reference junction, the thermocouple signal was conducted as a millivolt potential through two copper



1. PRIMARY HEAT EXCHANGER
2. SECONDARY HEAT EXCHANGER
3. APOLLO HEAT EXCHANGER
4. BYPASS VALVE
5. FLEX-HOSE COOLANT VALVES
6. SECONDARY COOLANT VALVE
7. PRIMARY AUTO-CONTROL VALVE
8. BYPASS VALVE
9. APOLLO COOLANT VALVE
10. FLEXIBLE HOSES
11. FLOWRATOR

A-9726

Figure 4. Coolant Distribution Schematic

wires to a Honeywell-Brown pen recorder. An increase in the amount of electrical current passing through the heating element of the mirror-copper base raised the surface temperature of the mirror immediately, vaporizing the dew, and thus leaving the instrument ready for dew-point measurement of another sample. The gas sample leaving the dew-point cell passed through a variable-area purgemeter, then through a diaphragm pump for return to its respective system. Trained personnel were able to operate the dew-point instruments reliably with an accuracy of ±1.0°F and a reproducibility of ±0.25°F.

Total and Differential Pressure Measurement

The total pressure measurements were made with absolute-pressure mercury manometers. The manometer pressures were corrected for temperature effects periodically during each test. Differential pressure measurements were made with gauge-pressure mercury manometers and with water manometers. Suit-to-cabin differential pressure was measured at the suit outlet quick-disconnect fitting. Suit inlet to suit outlet differential pressure was measured at the suit inlet and outlet quick-disconnect fittings.

Minute Volume Measurement

The respiratory minute volume was determined by passing the expired gas through a respiration gas meter (model 59, Max-Planck Institute for Work Physiology). This instrument was developed for determining the minute volume of humans performing various work loads, and it was ideally suited for this test program. The gas meter was encased in a pressure-tight cylindrical housing with a plexiglass window permitting a constant visual readout. Figure 5 shows the location of the flowmeter and other respiratory apparatus. Total pressure and dry-bulb temperature of the gas at the meter were monitored and accounted for in all quantitative measurements.

The inspiration gas was picked up at the helmet and ducted through a temperature-controlled flexible convoluted hose to a bifurcated mouthpiece, which was connected to the helmet visor by means of a quick-disconnect leak-tight fitting installed on the helmet visor. The bifurcated mouthpiece was formed in two halves, of 0.030-in.-thick free-machining brass, and plated with gold (MIL-G-45420), 0.010 in. thick, to minimize radiant heat transfer. The mouthpiece also was wrapped with independently controlled heating tapes and coolant tubes so that the inspiration and expiration systems could be maintained at the selected temperatures up to the mouth. An epoxy septum formed a leak-proof bond of the two halves and separated the inspiration and expiration systems, thus minimizing thermal conduction between the two systems at the mouth. This permitted an accurate determination of the true physical conditions of the inspired and expired gases. Upon inspiration, a low-pressure-drop inspiration check valve in the mouthpiece (pressure drop less than 0.5 in. of water) opened, allowing the inspiration gas to flow from the helmet into the mouth upon demand. Upon expiration, the inspiration check valve closed and the low-pressure-drop expiration check valve (pressure drop less than 0.5 in. of water) opened, allowing the expired gas to flow from the bifurcated mouthpiece, through a temperature-controlled flexible hose, to the respiration-gas meter for volumetric measurements. After the measurement of the expired gas volume,

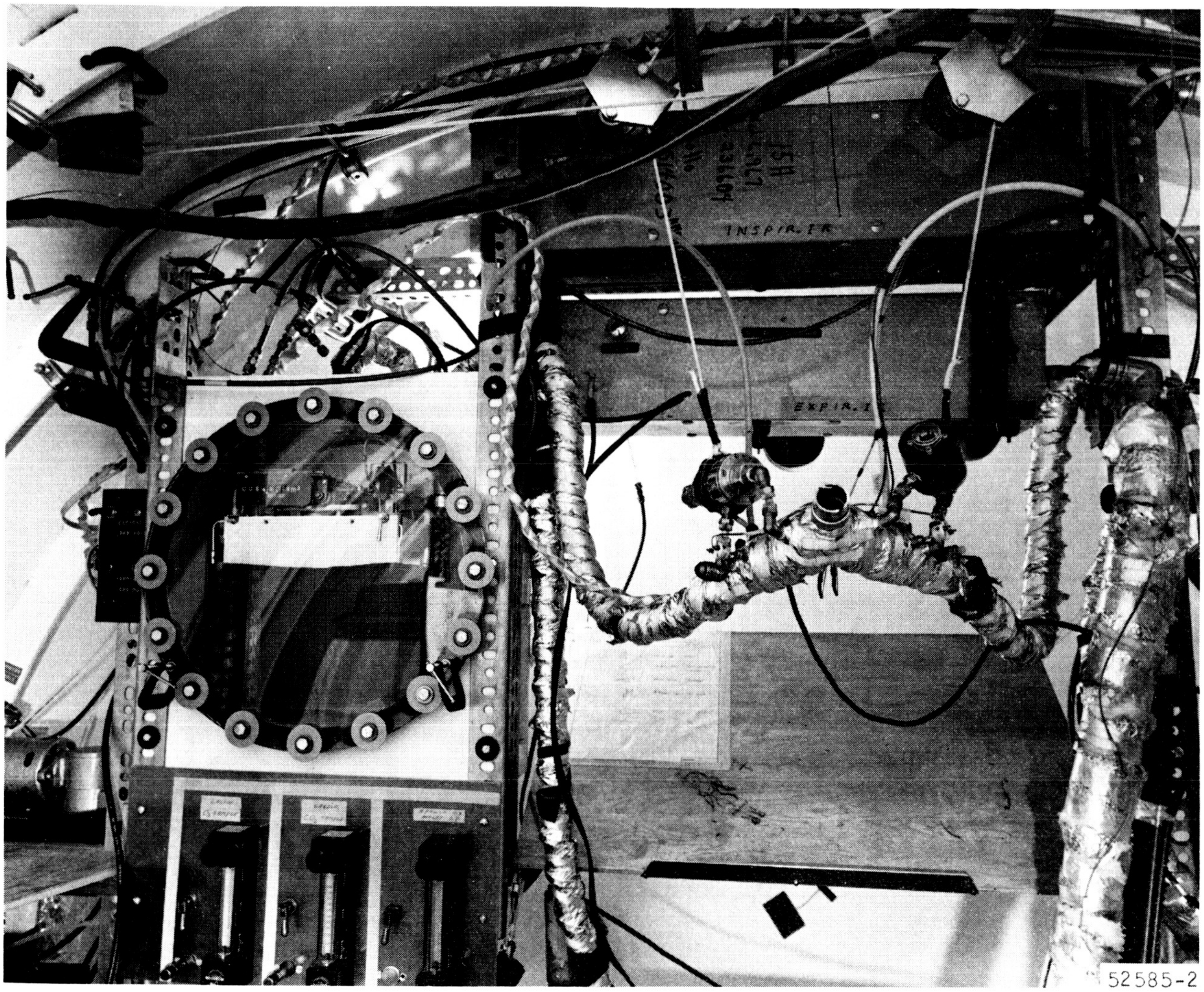


Figure 5. Flow Meter and Other Respiratory Apparatus

the gas was returned to the helmet where it was deflected away from the face and into the helmet ventilation stream. The respiration gas meter was calibrated frequently to assure an accurate and precise volumetric measurement. A schematic drawing of the respiratory circuit is shown in Figure 6.

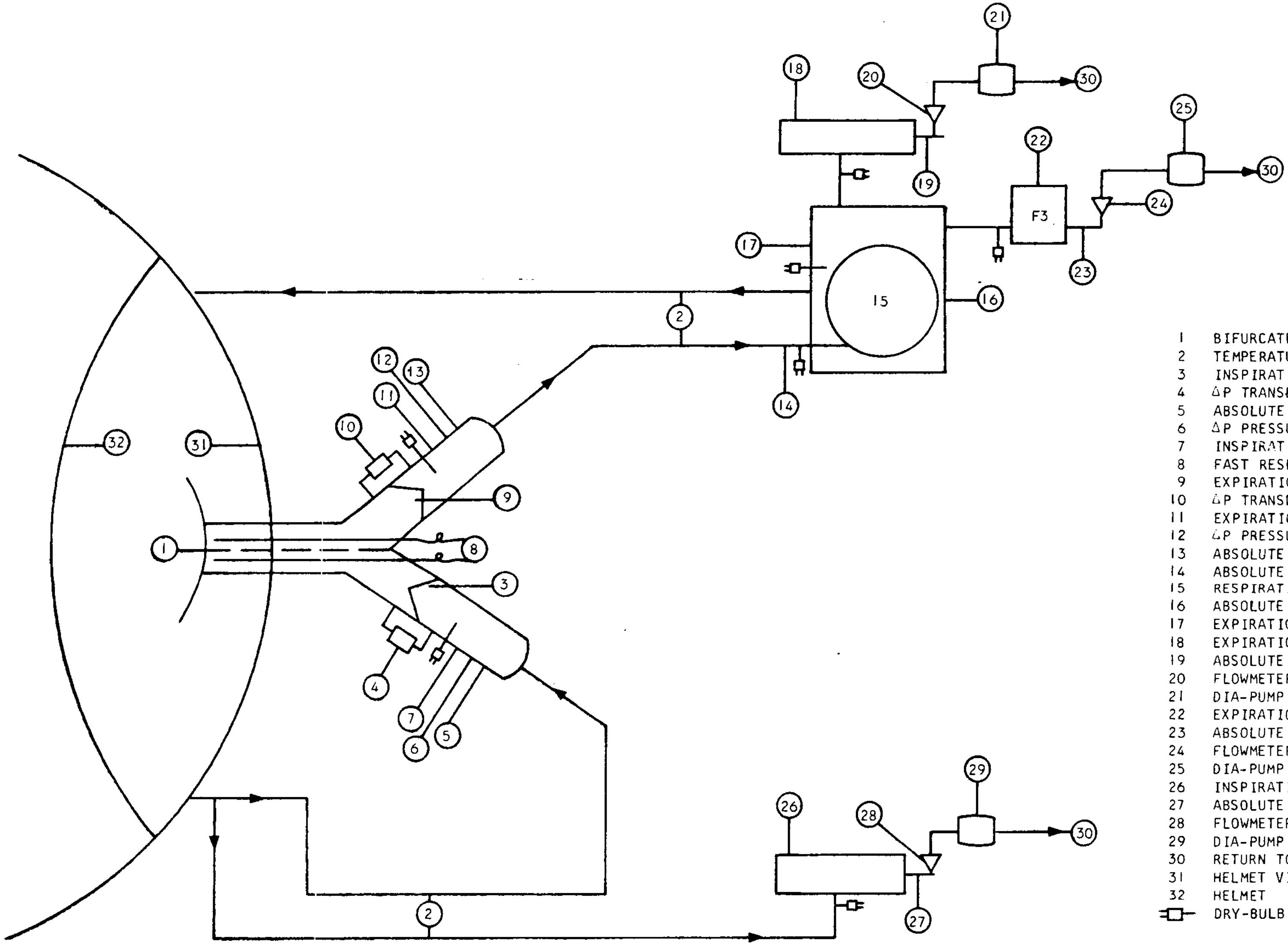
SUSPENSION OF THE MOUTHPIECE

The bifurcated mouthpiece was fitted inside the helmet with a rubber athletic-type mouthpiece, which was inserted into the subject's mouth. Because of the weight of the apparatus, the entire assembly was suspended by attaching two cords to the Δp transducers, which were situated at the center of gravity of the mouthpiece assembly. The cords were run through a series of pulleys attached overhead in the altitude chamber and secured to a suspension spring. The suspension spring, located near the top of the chamber, ran parallel to the floor and was anchored to a perforated plate by a wire hook so that it could be moved to any position along the plate, thus lowering or raising the mouthpiece and enabling it to be set at the proper elevation for each individual. The suspension spring allowed the mouthpiece assembly to move up and down with the subject's normal amplitude of vertical and horizontal oscillation during exercise on the treadmill. Figure 7 shows the subject wearing the mouthpiece.

ANALYSIS OF RESPIRATION GASES

The CO_2 and O_2 concentrations in the expired and inspired gases were analyzed with a Beckman IR15-A infrared analyzer and a Beckman F-3 paramagnetic analyzer, respectively. Samples of the expiration gas were picked up at the respiration-gas meter housing and ducted through a 1/4-in.-OD polyflow line to the expiration CO_2 analyzer, then to a variable area purgemeter located at the analyzer cell outlet port. From the purgemeter, the gas was picked up by a diaphragm pump that was located inside the altitude chamber and returned to the suit outlet system at a point upstream of the suit outlet laminar-flow meter. Samples of the inspiration gas were picked up at the helmet inspiration port and ducted through the inspiration CO_2 analyzer in the same manner as that used for the expiration sample.

The oxygen partial pressure was measured at the respiration-meter housing (in the expiration side of the respiratory circuit). The CO_2 and O_2 analyzers were calibrated prior to each test and after each change of altitude. The analyzers were calibrated at the same pressure and flow rates as those used during an actual analysis during test. Certified calibration gases were used to calibrate the analyzers. The expiration CO_2 analyzer and the O_2 analyzer were electrically connected to a Honeywell-Brown Electronik recorder for a precise readout. The inspiration CO_2 analyzer, however, was read directly from the meter at its amplifier, which was located outside the altitude chamber. The gas analysis circuit is shown on the schematic in Figure 6.



1	BIFURCATED MOUTHPIECE
2	TEMPERATURE CONTROLLED HOSES
3	INSPIRATION CHECK VALVE
4	ΔP TRANSDUCER
5	ABSOLUTE PRESSURE
6	ΔP PRESSURE
7	INSPIRATION DEW POINT
8	FAST RESPONSE THERMOCOUPLES
9	EXPIRATION CHECK VALVE
10	ΔP TRANSDUCER
11	EXPIRATION DEW POINT
12	ΔP PRESSURE
13	ABSOLUTE PRESSURE
14	ABSOLUTE PRESSURE
15	RESPIRATION METER
16	ABSOLUTE PRESSURE
17	EXPIRATION DEW POINT
18	EXPIRATION CO_2 ANALYZER
19	ABSOLUTE PRESSURE
20	FLOWMETER
21	DIA-PUMP
22	EXPIRATION O_2 ANALYZER
23	ABSOLUTE PRESSURE
24	FLOWMETER
25	DIA-PUMP
26	INSPIRATION CO_2 ANALYZER
27	ABSOLUTE PRESSURE
28	FLOWMETER
29	DIA-PUMP
30	RETURN TO SUIT EXHAUST SYSTEM
31	HELMET VISOR
32	HELMET
	DRY-BULB TEMPERATURE

B-2250

Figure 6. Respiratory and Gas Analysis System Schematic

Figure 7. Subject Wearing Mouthpiece

BIOINSTRUMENTATION

Skin Temperature

The temperature of the skin was measured with copper-constantan thermocouples and recorded on a 24-channel Brown-Honeywell recorder. The thermocouples were applied firmly with tape at the following locations (see Figure 8):

Anteromedial aspect of leg between knee and ankle

Medial aspect of thigh, midway between perineum and knee

Back, over supraspinatus muscle

Chest, 1 in. medial to nipple

Anterolateral aspect of upper arm, midway between shoulder and elbow

Posterior aspect of forearm, midway between elbow and wrist

Dorsum of hand

Forehead

Several attempts were made to measure temperature changes on the dorsum of the foot and on the tympanic membrane. These failed, respectively, because of the difficulty of keeping the foot sensor in place while the suit was being donned, and because the earpads inside the helmet exerted so much pressure on the tympanic sensor that the subjects complained of intolerable discomfort.

Rectal Temperature

Temperature changes in the rectum were measured with a thermistor probe (0.46 cm in diameter and 3.9 cm long) and recorded on an Offner Type S Dynograph. All rectal temperature probes were inserted approximately 10 cm beyond the anal sphincter.

Both skin and rectal temperatures were recorded automatically and continuously at sea level and at simulated altitudes.

Electrocardiograph

Continuous electrocardiograms were taken using a three-electrode system consisting of a bipolar modified V_4 lead and a ground. Recording and monitoring was done on the Dynograph; at 5-min intervals, the speed of the recording paper was increased from 1 mm/sec to 10 mm/sec to facilitate examination of the tracing.

Early in the test program an EKG signal was lost because profuse sweating and heavy exercise combined to loosen the chest lead. In subsequent tests, an Ace bandage was wrapped around the thorax with just enough pressure to hold the chest lead comfortably in place; this arrangement gave excellent results and virtually noise-free records even during maximum exercise.

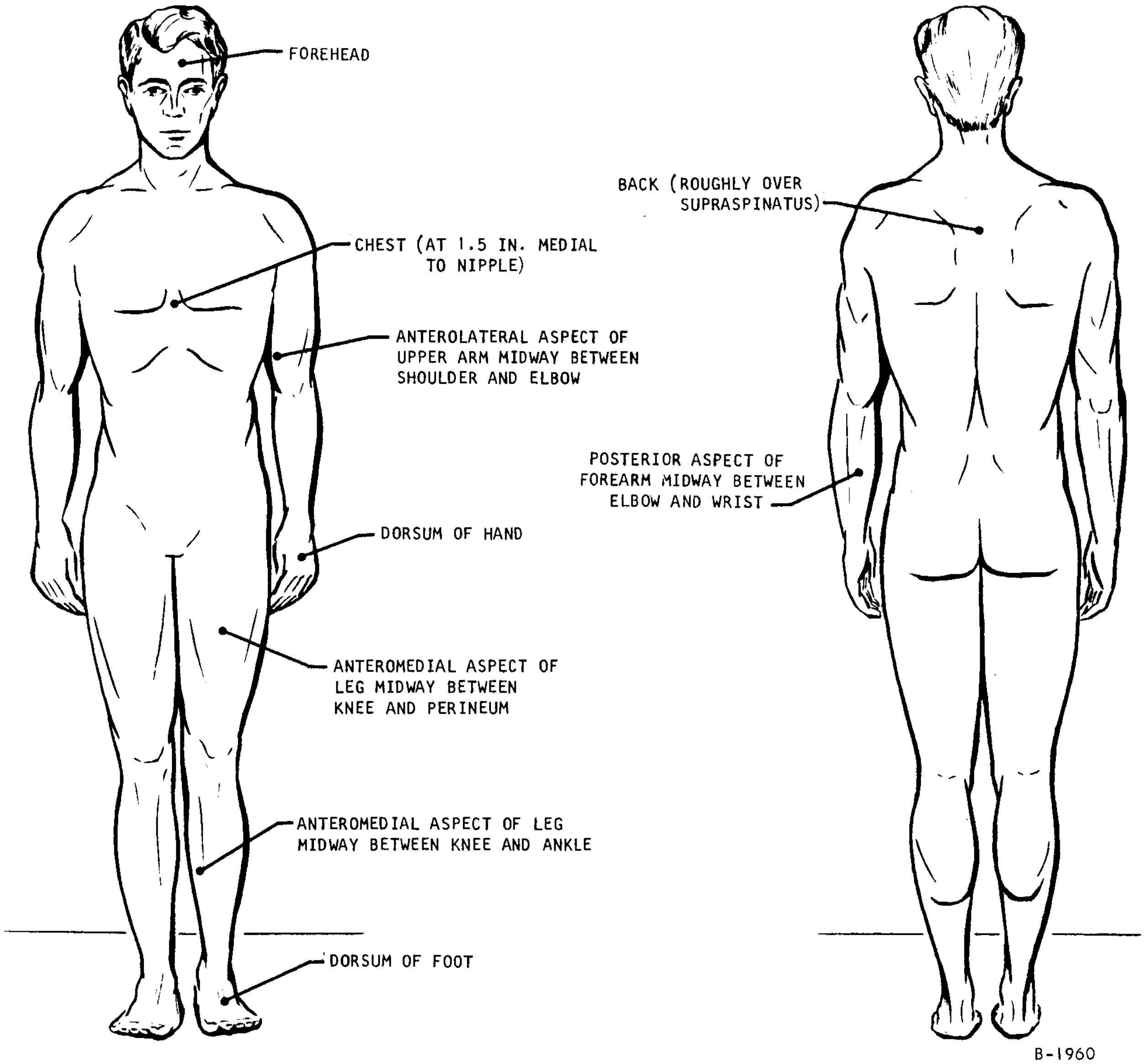


Figure 8. Skin Thermocouple Placement

Respiration

Respiratory rate was measured using short-time-constant thermocouples located in the inspiratory and expiratory chambers of the bifurcated mouthpiece, which was fitted into the port at the front of the helmet. Monitoring and recording of respiratory rate was done on the Dynograph.

Respiratory minute volume was determined by measuring the flow of expired gas through a respiration-gas meter (Model 59, Max Planck Institute for Work Physiology), which was located in the altitude chamber and read by the observer. Figure 5 shows the location of this instrument inside its pressure vessel.

SECTION 3

SUBJECTS

Ten male subjects were originally scheduled for this experiment. They were given thorough physical examinations and a high-altitude indoctrination. These men were in excellent condition, had a weight range of 130 to 164 lb, a height range of 66 to 69.5 in., and an age range of 21 to 34 years. During the indoctrination they were shown two movies on physiological changes that occur at high altitude, given an indoctrination lecture, instructed in the use of oxygen equipment for breathing at high altitude, and taken on test runs in the altitude chamber to 34,000 ft. Following this, eight subjects were selected to continue.

After the test program started, however, three of the initial eight subjects selected were unable to complete the first mode because of variety of subjective reasons such as "neck cramps", "trouble in breathing", "tired legs", and "great all-over body discomfort." This turn of events made it necessary to use three additional subjects. These men had a weight range of 133 to 166 lb, a height range of 68.75 to 70 in., and an age range of 30 to 36 years. All eight of these finally selected subjects completed the tests, but one complained of cramps in the thigh during one of the exercise modes, and that the suit was too tight around the crotch area.

SECTION 4

TEST PROCEDURE

PREPARATIONS

The subject, upon arrival at the test facility, received a medical examination and was weighed, and the bioinstrumentation was attached. The subject was then dressed in a waffle-weave undergarment and assisted in donning the pressure suit. Immediately after the pressure suit was donned, an AiResearch portable suit cooler was connected to the suit inlet fitting to keep the subject comfortable and dry. Figure 9 shows the subject dressed and the portable cooler connected to the suit. This procedure normally preceded the connection of the internal bioinstrumentation to the suit quick-disconnect fitting designed for that purpose. The boots and gloves were then attached and the pressure zipper was closed. The subject, together with the portable cooler, was then taken into the altitude chamber. In the altitude chamber, the subject donned a five-layer reflective mylar coverall and was connected to the environmental control system. The suit-outlet fitting was connected, the portable cooler was removed, and the inlet fitting from the environmental control system was connected. The bioinstrumentation and communication quick-disconnect fitting was then mated, a nose clamp was placed on the subject's nose, and the helmet was donned and locked in place.

Following checkout of the communications and bioinstrumentation, the gas-collection and return hoses and the bifurcated mouthpiece were connected to the helmet. The subject then took the flexible mouthpiece (the flexible mouthpiece was permanently attached to the inner surface of the helmet visor) into his mouth, and the height of the respiratory apparatus was adjusted for comfort. At this point, final calibrations were made and the first test period was ready to commence. Figures 7 and 10 show the subject in the suit, fully instrumented, and ready to commence exercising on the treadmill.

SEA LEVEL TESTS

The suit was pressurized and ventilation inlet conditions were adjusted to 17.1 cfm, 33°F dew-point, and 76°F dry-bulb temperature, and the first test period commenced with the actuation of the treadmill and its adjustment to 1.4 mph (1.2 mph indicated). The subject was required to walk at this speed for a period of 1 hr, or until exhaustion, equipment failure, or the physiological parameters monitored indicated that further exercise was dangerous. Normally the criteria for termination of exercise was a pulse rate of 200 or a rectal temperature in excess of 103°F. Figure 11 shows the subject at exercise on the treadmill.

At the end of this test mode the treadmill was stopped, the suit partially depressurized, and the subject seated. The subject was allowed to rest for at least 30 min. During this period the subject did not breathe through the mouthpiece.

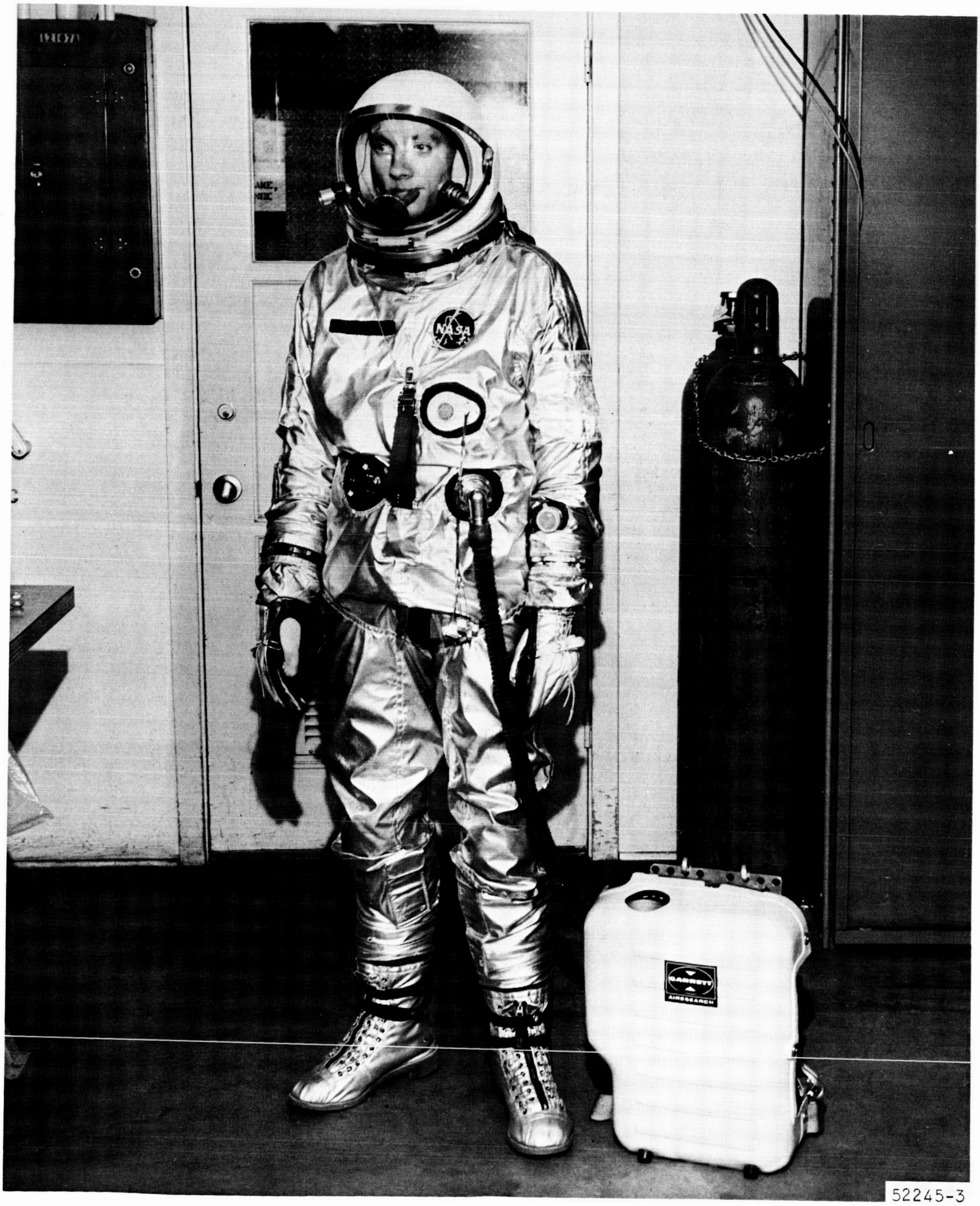


Figure 9. Subject with Suit and Cooler

Figure 10. Subject in Test Position

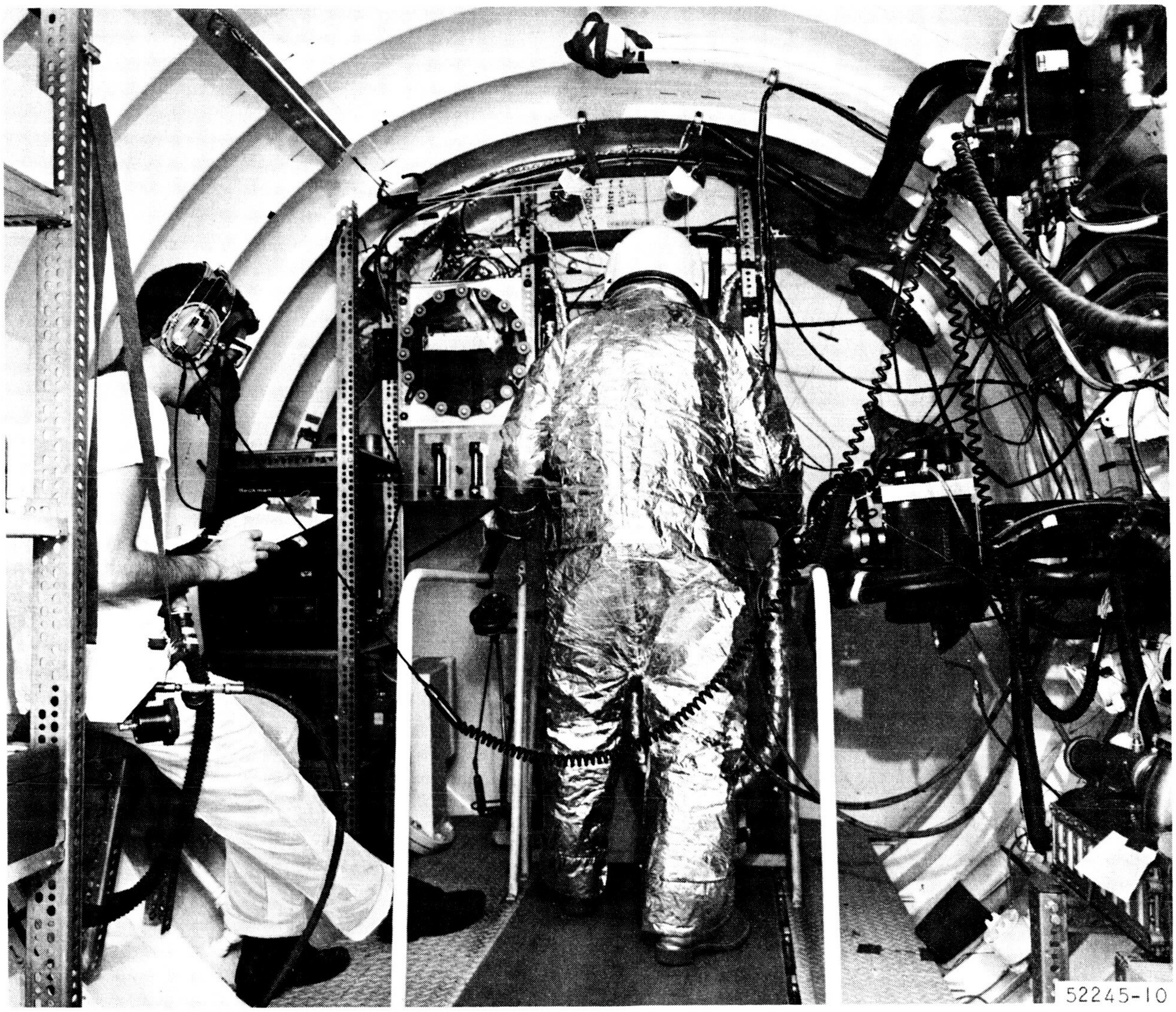


Figure 11. Subject Exercising on the Treadmill

Following the test period, the subject stood up on the treadmill and resumed breathing through the mouthpiece; the treadmill was activated and the speed adjusted to 2.0 mph; and the suit ventilation inlet conditions were adjusted as before. The duration of this period was the same as that indicated for the 1.4-mph test.

ALTITUDE TESTS

Following another rest period of approximately 1 hr, during which the chamber pressure was reduced to tne equivalent of 32,500 ft altitude and the apparatus recalibrated, the subject was prepared for another test mode. The suit was pressurized to 3.7 psig (7.6 psia) and inlet conditions were adjusted to 17.1 cfm, 50°F dry-bulb, and 33°F dew-point temperature, and the treadmill set at 1.4 mph (1.2 indicated). The subject was then required to exercise at tnis speed until tne criteria for test mode completion, discussed above, were reached.

Following this test period the subject was again allowed to rest for at least 30 min. This rest period was followed by the final test mode, which was identical to the preceding mode, except that the treadmill was adjusted to a speed of 2.0 mph. The completion of this test mode resulted in the termination of testing for that day. The altitude chamber was returned to ambient pressure, and the subject was removed, weighed, interviewed, and medically examined. Figure 12 shows the subject leaving the altitude chamber following the testing.

DATA COLLECTION

Most of the data were recorded continuously in analog form, or in digital printout every 15 sec. Data used to evaluate the results of the experiment, however, were collected at 5-min intervals throughout each test period. To facilitate this method of collecting data, all recorders were equipped with automatic markers that indicated both 1-min and 5-min intervals. In addition, a bell was initiated by the 5-min marker pulse. This bell served as a signal for both the data collectors and the observer in the altitude chamber, so that data on all parameters could be collected simultaneously. Data collection was further facilitated by the use of special data collection forms. These forms, samples of which are contained in the Appendix, were designed so that the data could be IBM keypunched and ready for computer processing without further transcription.

Figure 13 shows the method used for collection of data on dew point. The suit flowmeter manometers used to ascertain the suit inlet and outlet flow rates are also shown. The technician in the foreground is using correction tables for the manometer indications to ascertain actual flow rates. Figure 14 shows the remainder of the data collectors and the tank operator. Figure 15 shows the medical monitor and examples of some of the physiological data collected during this experiment.

Figure 12. Subject Leaving Altitude Chamber

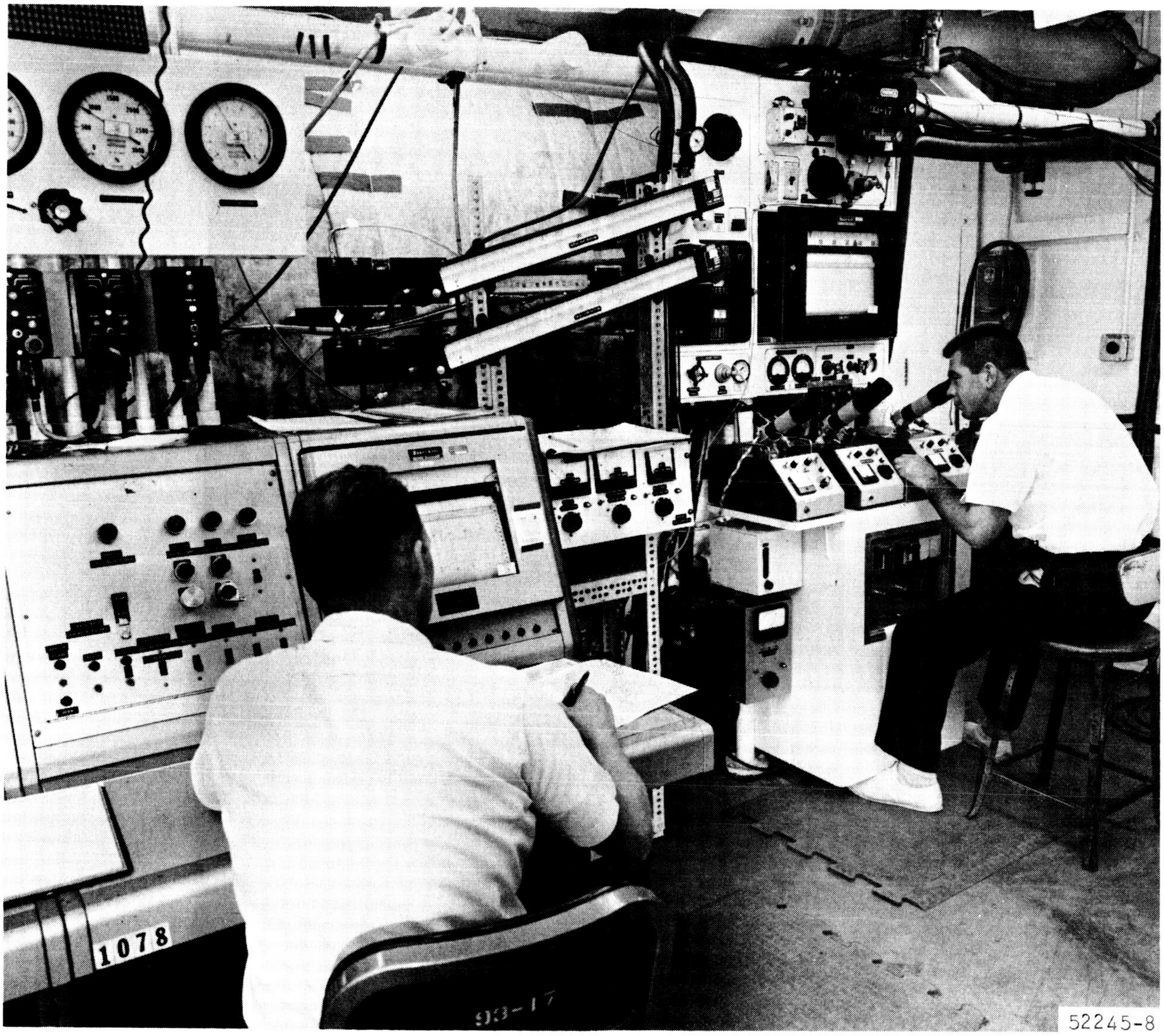


Figure 13. Dew-Point Measurement

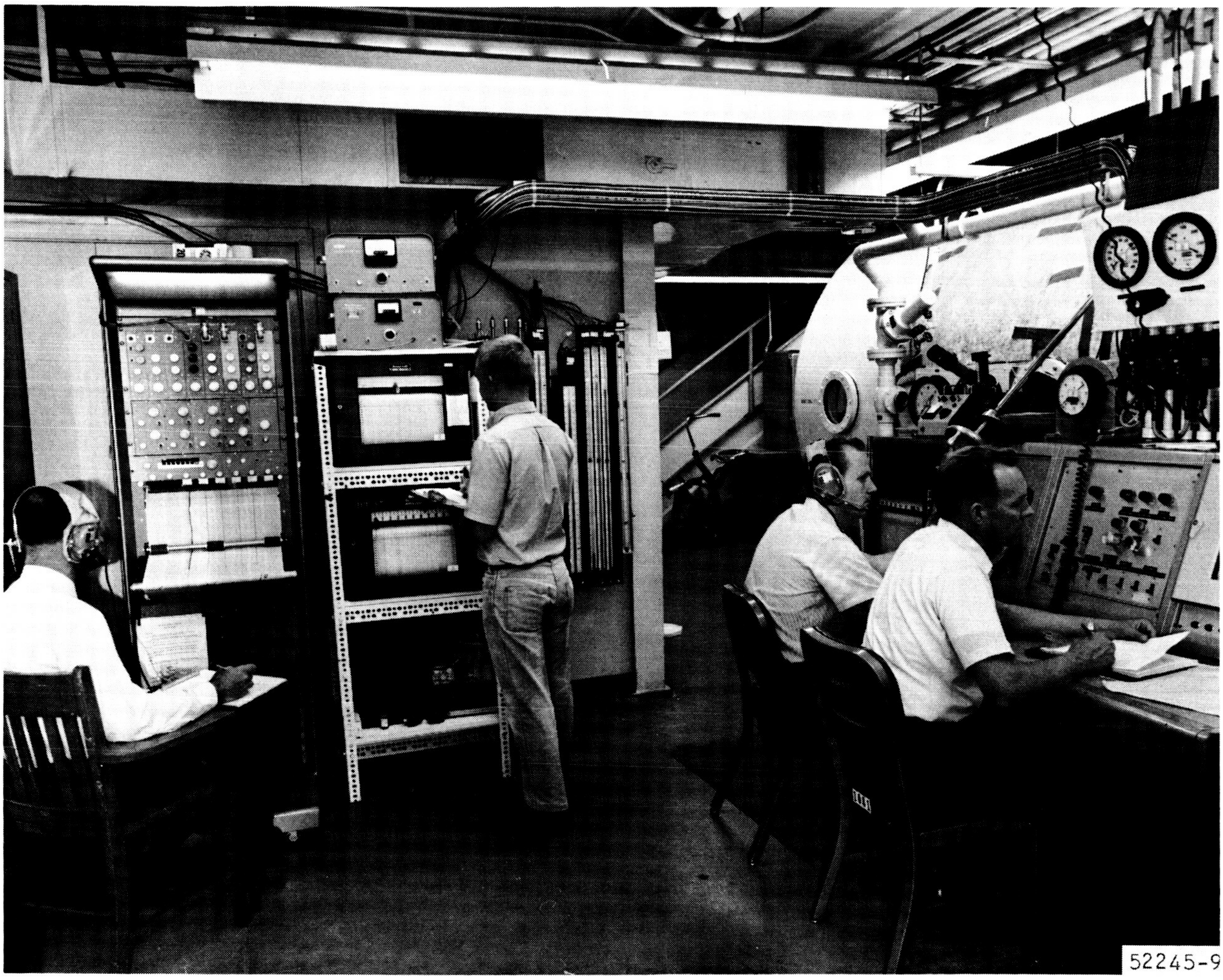


Figure 14. Tank Operator and Data Collectors

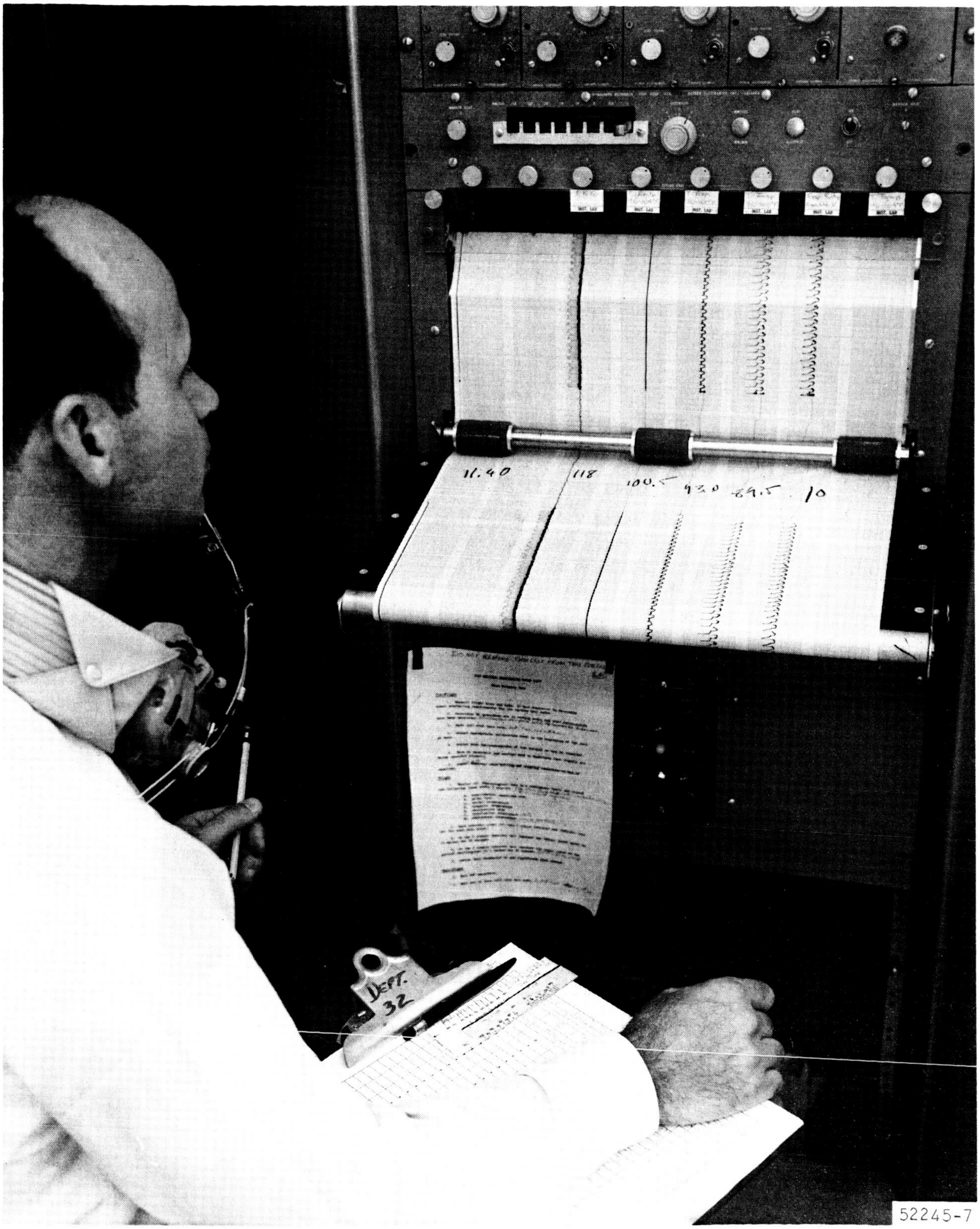


Figure 15. Test Medical Monitor

SECTION 5

DATA REDUCTION AND ERROR ANALYSIS

COMPUTATIONAL PROCEDURES

As previously mentioned, the raw data were collected during this experiment at intervals of 5 min, and sufficient personnel and recording equipment were employed so that all the data could be recorded for a single point in time. The data were recorded directly from the instruments on data sheets prepared for IBM keypunch operations (see Appendix), and were subsequently keypunched and entered, along with a preprogram, in an IBM 7074 computer. At all points of listing, the consistency of time, test conditions, subject designation, and date were compared for accuracy. The results obtained and presented in this report have been cross-checked with all pertinent control points to assure proper comparative data. The computer presented all data required for interpretation or subsequent analysis, whether or not these data were required for the computations. The following paragraphs further illustrate the use of the computer and the data recording sheets.

Each test condition required six data sheets, which are identified by the first digit on the heading. Each sheet also contained the test mode code, date, and subject's initials for further identification. Water removed and treadmill speed were listed for comparative purposes to maintain consistency among the data points.

The desired parameters which required computations from the raw data were:

Metabolic rate, Btu/hr

Latent heat removal, both respiratory and suit, Btu/hr

Sensible heat removal, both respiratory and suit, Btu/hr

Total heat removal, Btu/hr

Body heat storage, Btu/hr

Respiratory heat loss, Btu/hr

Mean body temperature, ^{0}F

Average skin temperature, ^{0}F

Pressures, volumes, and temperatures were corrected to standard conditions prior to final calculations.

The equations used to determine the above parameters are given in the following paragraphs.

Metabolic Rate

The equation for metabolic rate is taken from G. Lusk (Reference 7), and simplified to the following form.

$$MR = K\, V_s (1.233\, RQ + 3.814) \text{ Btu/hr}$$

where K_1 = constant

V_s = liters of oxygen consumed at standard conditions

$$RQ = \frac{\text{Volume of carbon dioxide produced}}{\text{Volume of oxygen consumed}}$$

$$V_s = (P_{o_{in}} - P_{o_{out}}) V_m \times \frac{T_s}{T_g P_s}$$

where P_o = partial pressure of oxygen, mm Hg

V_m = minute volume, liters/min

T_g = temperature of gas, ^0R

T_s = 492^0R

P_s = 760 mm Hg

$$P_{o_{in}} = (P_t - P_w - P_c)$$

where P_t = total pressure

P_w = water vapor pressure

P_c = carbon dioxide pressure

The respiratory quotient (RQ) was determined for each point, and if it was less than 0.7 or greater than 1.0, a value of 0.86 was used.

Latent Heat Removal

The equations used for determining the latent heat removed are based on inlet and outlet vapor pressures and dry-bulb temperatures. The total enthalpy of the water vapor at dry-bulb temperature is used, since this value multiplied by the calculated weight at the existing dew-point temperature will include the heat of vaporization and the superheat of that mass of water above the dew-point temperature. The equation is

$$LH \text{ (Latent Heat Transfer)} = W_{out} h_{tdbo} - W_{in} h_{tdbin}$$

where $W_{out} = \dfrac{KV_{out} \times P_{t_{out}}}{T_{out}} \times \dfrac{VP_{out}}{P_t - VP_{out}}$

K = constant of proportionality including molecular weights, pressures, and temperatures

W_{in} = the same as above under inlet conditions

h_{tdbo} = total enthalpy of water vapor at dry-bulb temperature, out

h_{tdbin} = total enthalpy of water vapor at dry-bulb temperature, in

V_{out} = suit ventilation

$P_{t_{out}}$ = total pressure

T_{out} = absolute temperature

VP_{out} = vapor pressure

Vapor pressures are determined in a computer subroutine that selects a vapor pressure best fitting an equation of vapor pressure in terms of dew-point temperature.

The calculation of respiratory latent heat removal is similar for the suit circuit. Total heat removed from the suit is the sum of both suit and respiratory circuits because the test setup provided the accumulation of both circuits at the suit outlet.

Sensible Heat Removal

The sensible heat removed was determined by computing the mass flow and multiplying by the specific heat of the gas and the change in temperature. The equation is

$$SH \text{ (Sensible Heat Transfer)} = W_{out} C_p T_{out} - W_{in} C_p T_{in}$$

Since $W_{out} \approx W_{in}$ and $C_{p_{in}} \approx C_{p_{out}}$, this equation can be written as

$$SH = W_{out} C_{p_{out}} (T_{out} - T_{in})$$

The subscripts may be changed without appreciable error since the combination of specific heats and mass flow are nearly equal.

Total Heat Removed

The total heat removed is equal to the sum of latent heat, sensible heat, and the accumulation of pumping losses as follows:

$$Q_t = Q_{lat} + Q_{sens} + Q_{pump}$$

$$Q_{pump} = 0.401 \ V \times h$$

where 0.401 = constant of proportionality

V = volume flow rate in cfm

h = pressure drop from inlet to outlet in in. of water

Heat losses or gains to ambient conditions were minimized by controlling air and cabin wall temperatures. Reflective coveralls consisting of five layers of aluminized mylar further reduced this heat transfer potential to a negligible amount. No other heat losses or gains were considered, except for small variations in the ambient temperature.

Inspired Carbon Dioxide

Inspired carbon dioxide was measured by an infrared analyzer calibrated for carbon dioxide and recorded as nonoxygen on data sheet 3. The inspired air consisted of a mixture of the respired gases and the suit ventilation gas.

Body Heat Storage

Body heat storage was determined by the equation

$$Q_{storage} = W_B C_B \Delta T = \text{heat storage, Btu/hr}$$

where W_B = weight of subject, lb

C_B = specific heat of the body = 0.83 Btu/lb-^{o}F

ΔT = change of temperature with respect to time, ^{o}F/hr

This equation is applicable to body mean temperature or core temperature. With a large variation in heat storage rate or high muscular activity, rectal temperature lags behind the limiting temperature and instantaneous calculation. Lag or lead by the estimating parameter influences finite calculations and predictions for the intervals used in the test. Thus, even though heat storage was computed for the total duration of each test mode, the calculations are not considered adequate because of the high level of muscular activity.

ERROR ANALYSIS

The measurement accuracies listed in Table I are weighted accuracies, converted to percentages for convenient use in the instrument error analysis. Some errors are incremental, such as the error in reading a mercury manometer regardless of total pressure. Oxygen partial pressure measurements are within 1 percent of the instrument full-scale deflection; since the instrument was recalibrated for each change in total pressure in order to read nearly full-scale, the 1-percent accuracy remains approximately correct.

TABLE I

INSTRUMENT ERROR

Parameter	Instrument	Accuracies(%)
Dew-point temperature	AiResearch-designed dew-point indicator	±1.0
Gas temperatures	Thermocouples-to-recorder	±0.8 (for ^oF) ±0.14 (for ^oR)
Gas pressures	Mercury manometers	±1.0
Partial pressure of oxygen	Paramagnetic analyzer	±1.0
Carbon dioxide volume, percent	Infrared analyzer	±1.0
Expired gas volume	Max Planck respiration gas meter	±2.5
Rectal temperature	Thermistor-to-recorder	±1.0
Suit volume flow	Laminar-flow flowmeter	±0.5

Using the accuracies listed in Table I, the relative errors introduced for each parameter (u) would be $\Delta u/u$; and Δu is equal to the percent accuracy times u/100. The accuracies listed are symmetrical, and no allowance for offsetting errors is made.

Error in Determining Metabolic Rate

The error in determining metabolic rate was calculated by

$$\Delta MR = K_1 V_s (1.233\ RQ + 3.814)(a + b)$$

where a = accuracy of determining V_s

b = accuracy of determining RQ, and

$$V_s = (P_{o_{in}} - P_{o_{out}})\, V_m \times \frac{T_s}{T_g P_s}$$

If c = accuracy of $P_{o_{in}}$, d = accuracy of $P_{o_{out}}$, e = accuracy of V_m, and f = accuracy of T_g, then $\Delta V_s = (c + d + e + f)\, V_s$, and $P_{o_{in}} = (P_t - P_w - P_c)$. Let g = accuracy of P_t, h = accuracy of P_w, and R = accuracy of P_c, then

$$\Delta P_{o_{in}} = (g + h + k) P_{o_{in}}, \text{ and } \frac{\Delta P_{o_{in}}}{P_{o_{in}}} = c = g + h + k.$$

Substituting the values from Table I into the above equation as relative errors rather than percentages,

$$c = g + h + k = 0.01 + 0.01 + 0.01$$

$$c = 0.03$$

$$a = c + d + e + f = 0.03 + 0.01 + 0.025 + 0.0014$$

$$a = 0.0664$$

Since $RQ = \frac{V_{CO_2}}{V_S}$, and the parenthetical expression is multiplied by V_s, the error introduced by RQ will be approximately that of determining V_{CO_2}; in addition, since it applies to one term only, a proportional reduction should be made as follows:

$$V_{CO_2} \approx 0.01 \times \text{Vol\%} \times V_m$$

Vol% is measured volume, percent, and V_m is the minute volume; therefore $b' = 0.01 + 0.025 = 0.035$, and $b = \frac{b'}{3} = 0.012$.

The error in determining metabolic rate is $(a + b) = 0.0784$, or approximately ±7.8 percent.

The error in determining RQ is ±10 percent.

Error in Determining Latent Heat Removal

The computer program used for data reduction contains several data references for computations not required in this study. In order to simplify calculations without a major change or addition of complexity, a reference temperature and an enthalpy of water vapor value used for other computations were selected. This selection produced latent heat removal approximately 5 percent lower than actual. This value is incorporated in the error analysis shown below.

$$LH = W_{out} h_{tdbo} - W_{in} h_{tdbin}$$

The error introduced here occurs in the determination of the weights. The error is identical in each case.

$$\Delta W = \frac{K_I V_x P}{T} \times \frac{VP}{P - VP} (a + b + c)$$

where $\frac{P}{P - VP} \approx \frac{P}{P}$ (and the error introduced by total pressure is negligible)

a = error due to volume determination

b = error in temperature

c = error in vapor pressure (dew-point)

Selecting the accuracies listed in Table I,

$$\Delta W = (0.5 + 0.14 + 1.0)W,$$

or the error is ±1.64 percent for each weight, and the error in latent heat removed is ±3.28 percent due to instrument errors.

As noted above, the 5 percent error is not symmetrical, and therefore the total error in latent heat is +3.28 percent and -8.28 percent.

Error in Determining Sensible Heat Removal

The sensible heat removal error is calculated by

$$SH = W_{out} C_p T_{out} - W_{in} C_p T_{in}$$

where $W = K \times \frac{VP}{T}$

Since the temperature appears in the numerator and the denominator, the error introduced is by volume and pressure measurement, and the error is $2(.5 + 1.0) \approx \pm 3.0$ percent.

Other Sources of Error

Potential errors not included in the above analysis are:

a. Calibration of instruments

b. Variation in calibration gases

c. Sampling methods

d. Human errors in reading and recording

These errors are of secondary effect or of random nature, and were not subjected to error analysis.

SECTION 6

RESULTS

The results of this experiment are summarized in the following subsections. These subsections are generally organized according to dependent parameter, and contain data in tabular and graphical form, together with a brief discussion of each parameter. The graphs are plots of the variable against the time elapsed from the start of the test mode. The dependent variable is plotted along the ordinate, and the elapsed time is plotted in intervals of 5 minutes along the abscissa. In each graph, the curves shown at left represent the data for the 1.4-mph walking rate, and those on the right are for the 2-mph walking rate.

MEANS FOR END-OF-RUN DATA POINTS

The point in time of greatest interest is the last data point for each experimental mode. The tables in this subsection show the average values of this last data point for all subjects and for each test mode. Table 2 presents the mean final metabolic rate. The metabolic rates for the exercise level of 1.4 mph are approximately the same for both sea level and altitude modes. At the higher level of work, 2.0 mph, however, a higher final metabolic rate was observed at altitude than at sea level. This higher metablic rate is believed to be due to both the "Q_{10} effect" on metabolism resulting from the higher rate of heat storage observed for this condition and the variance in the data.

The mean final net heat removal rates shown in Table 3 indicate that the sea level and altitude suit-ventilation inlet conditions resulted in almost identical heat removal rates.

Tables 4 and 5 present the breakdown of the final total heat removal into the final latent and sensible heat removals, respectively.

The most illustrative tabulation of the effects of the factors at work in this experiment is that presented in Table 6. This table shows the ratios of the mean final net heat removed from the suit to the mean final metabolic rate. This ratio, which may be considered an index of heat removal efficiency, indicates that there was a decrease in heat removal efficiency as metabolic rates increased, for a given set of inlet conditions. It also indicates that there was an additional decrease in heat removal efficiency at reduced pressure, even though the suit inlet conditions were altered in an attempt to eliminate the effect of reduced ventilation mass flow. This should be contrasted with the previously stated observation that the final heat removals are almost identical for altitude and sea level conditions.

The mean final suit outlet dry-bulb and dew-point temperatures are given in Tables 7 and 8, respectively. The values in both tables show that there are considerable differences between the outlet temperatures at sea level and at altitude. Metabolic rate, however, seems to have little effect on these two parameters.

Rectal temperatures (Table 9), on the other hand, show exactly the opposite response. Metabolic rates demonstrate an effect on rectal temperature, while the differences between sea level and altitude conditions appear to have little or no effect.

The effect of the variables on final minute volume is shown in Tables 10 and 11. It is obvious from the latter that minute volume was reduced at altitude. This is consistent with previous observations at the AiResearch R & D laboratory for subjects breathing pure oxygen. (Reference 8)

The final table, Table 12, contains the observations on heart rate. The usual effect of work rate is noted, while the altitude mode conditions appear to have no effect on this parameter.

TABLE 2

MEAN FINAL METABOLIC RATE, BTU/HR

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	2047	2347
Altitude	2092	2703

TABLE 3

MEAN FINAL NET HEAT REMOVED, BTU/HR

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	1331	1342
Altitude	1186	1407

TABLE 4

MEAN FINAL LATENT HEAT REMOVED FROM SUIT, BTU/HR

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	1141	1196
Altitude	920	1182

TABLE 5

MEAN FINAL SENSIBLE HEAT REMOVED FROM SUIT, BTU/HR

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	308	271
Altitude	304	327

TABLE 6

RATIO MEAN FINAL NET HEAT REMOVED/MEAN FINAL METABOLIC RATE

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	0.65	0.57
Altitude	0.57	0.52

TABLE 7

MEAN FINAL SUIT OUTLET DRY-BULB TEMPERATURES, °F

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	86.54	85.98
Altitude	82.53	83.25

TABLE 8

MEAN FINAL SUIT OUTLET DEW-POINT TEMPERATURES, °F

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	74.14°F	75.08°F
Altitude	67.25°F	70.80°F

TABLE 9

MEAN FINAL RECTAL TEMPERATURE, °F

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	101.2	101.97
Altitude	101.3	102.08

TABLE 10

MEAN FINAL MINUTE VOLUME, L/MIN (A.T.P.)

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	31.46	34.14
Altitude	25.53	32.60

TABLE 11

MINUTE VOLUME ADJUSTED FOR METABOLIC RATE
(100 Mean Final Min Vol/Mean Final Q_M)

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	1.52	1.45
Altitude	1.22	1.21

TABLE 12

HEART RATE, BEATS/MIN

Pressure	Work Rate	
	1.4 MPH	2.0 MPH
Sea Level	143	163.9
Altitude	135	170

METABOLIC RATE

This subsection presents graphs of the metabolic rate data for each test. In addition to the observed metabolic rates, curves are presented which correct the metabolic rate for Q_{10}, and for both Q_{10} and work. The Q_{10} correction is to adjust the metabolic rate for the effects of body heat storage. The factor employed for correction is 13 percent for each $1^{o}C$ rise in rectal temperature.

For each of the figures in this section (Figures 16 through 33) the graph on the left represents data taken at 1.4 mph while the curves to the right are for observations at 2.0 mph.

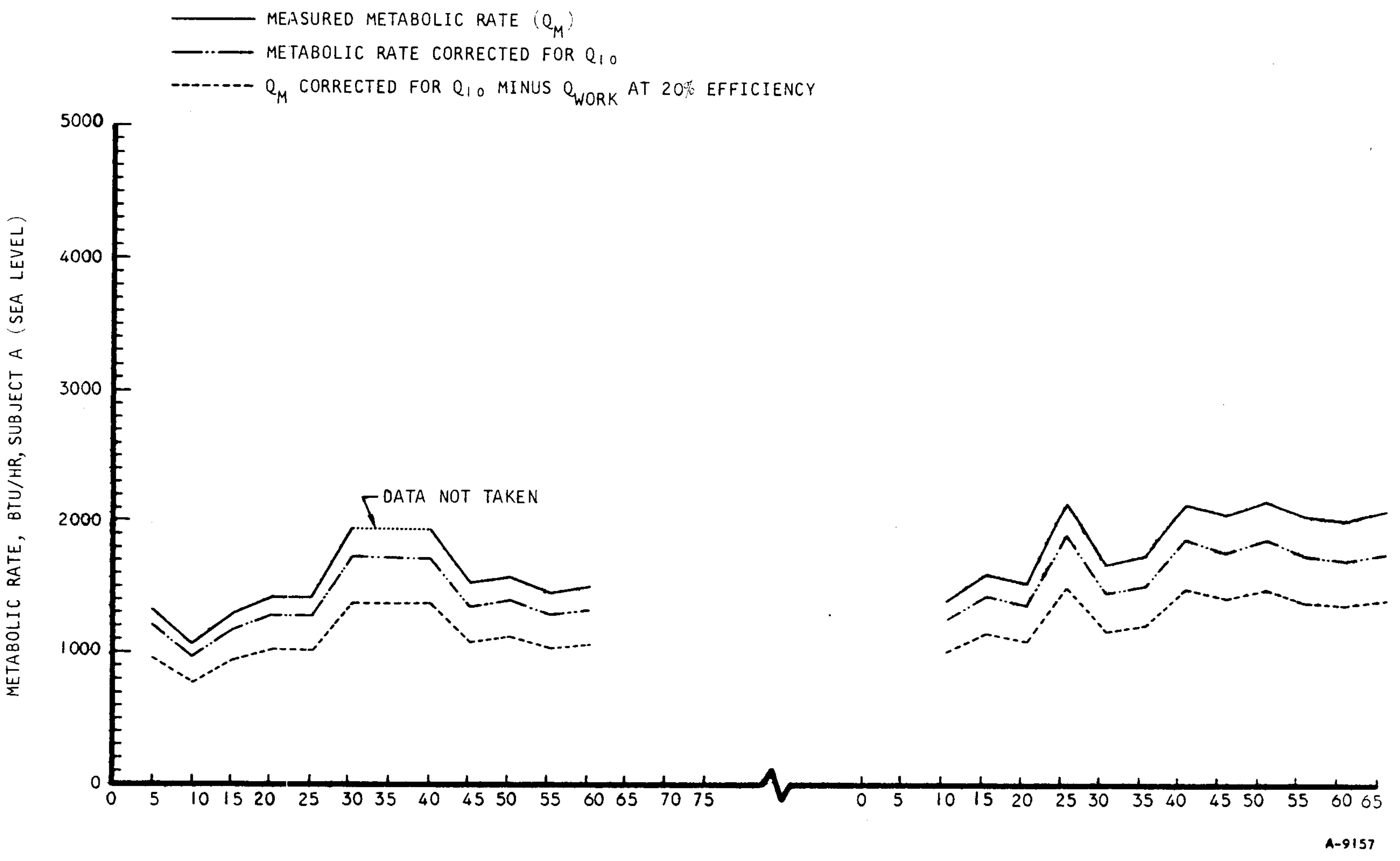


Figure 16. Metabolic Rate, Subject A (Sea Level)

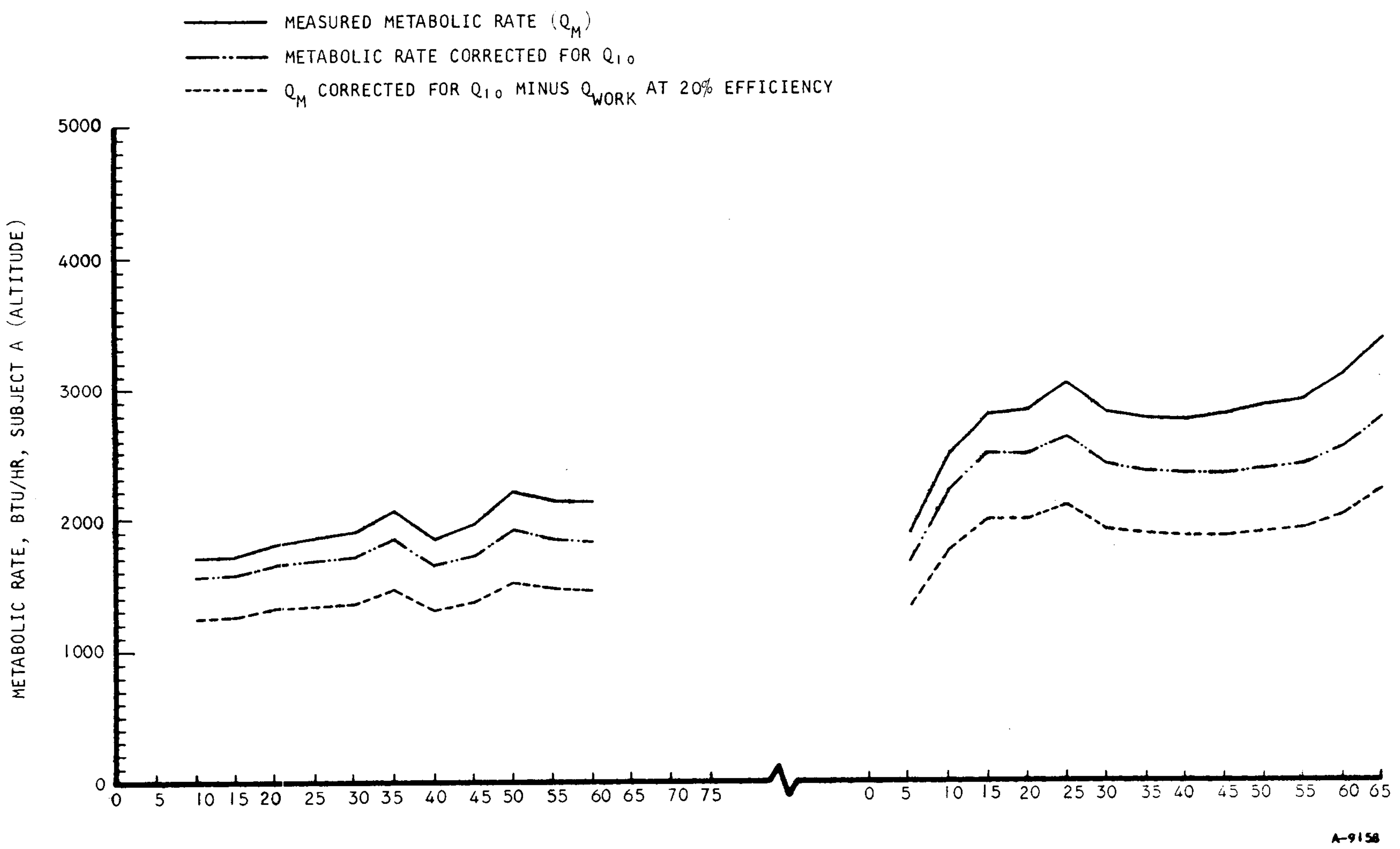


Figure 17. Metabolic Rate, Subject A (Altitude)

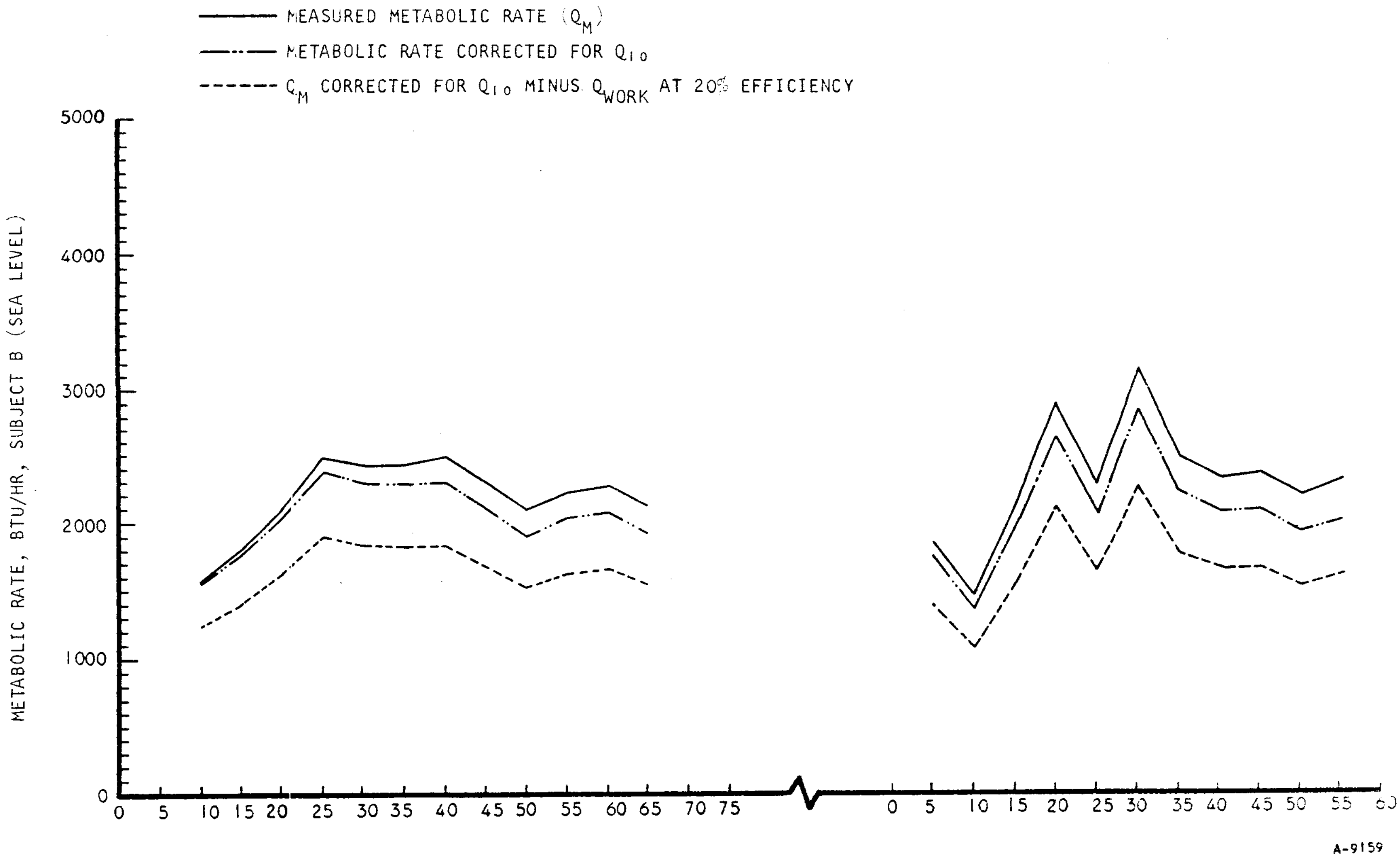


Figure 18. Metabolic Rate, Subject B (Sea Level)

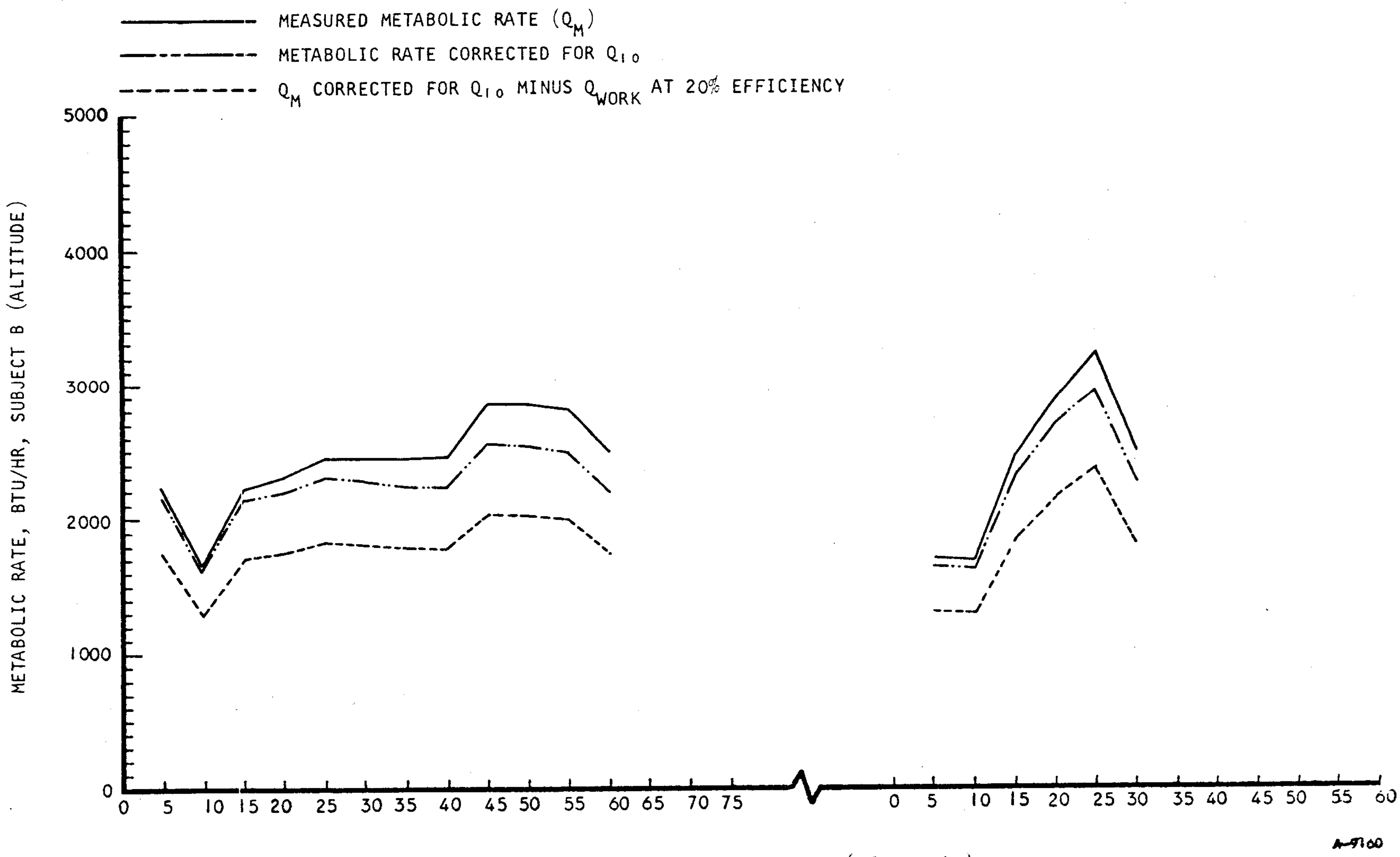


Figure 19. Metabolic Rate, Subject B (Altitude)

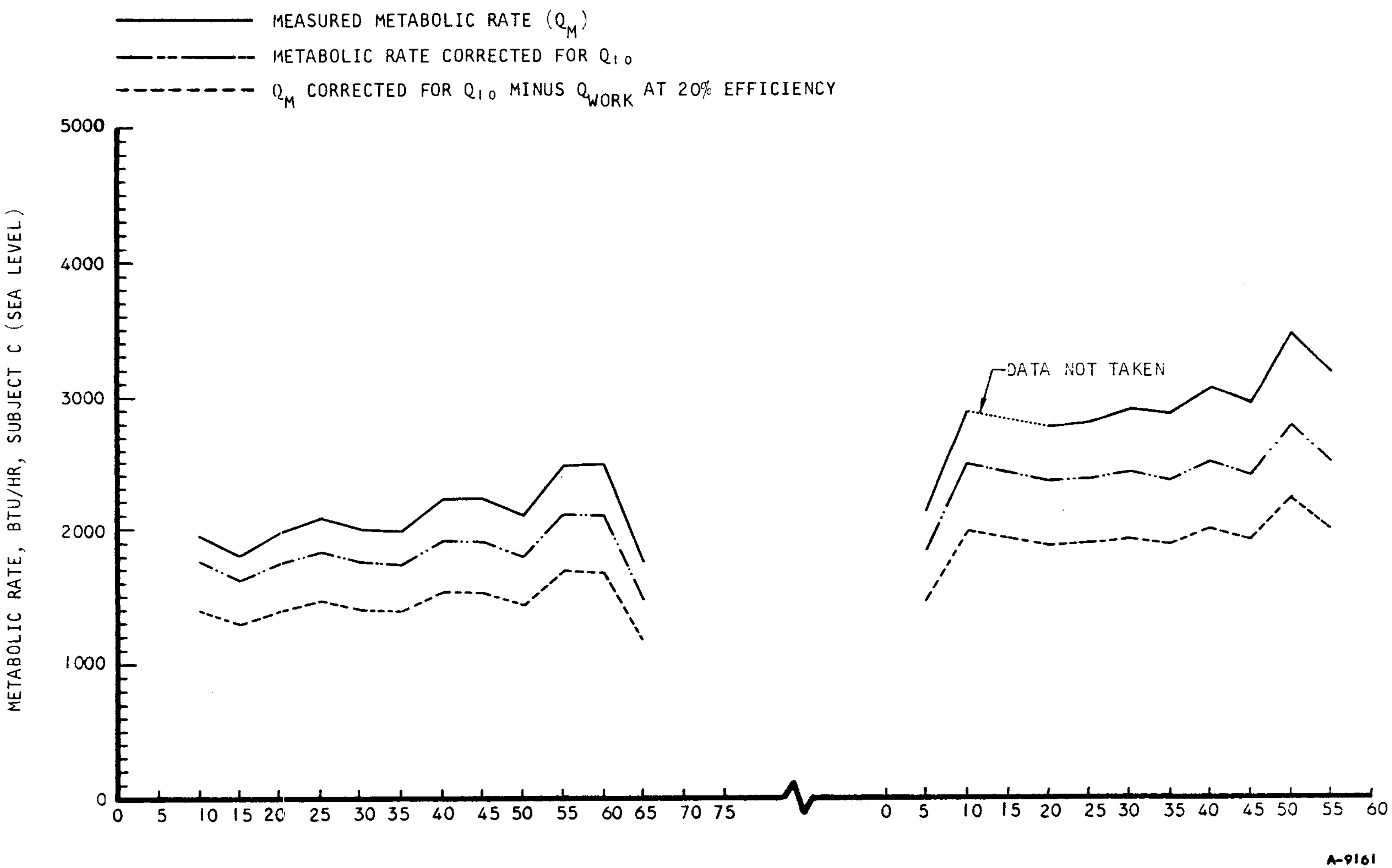


Figure 20. Metabolic Rate, Subject C (Sea Level)

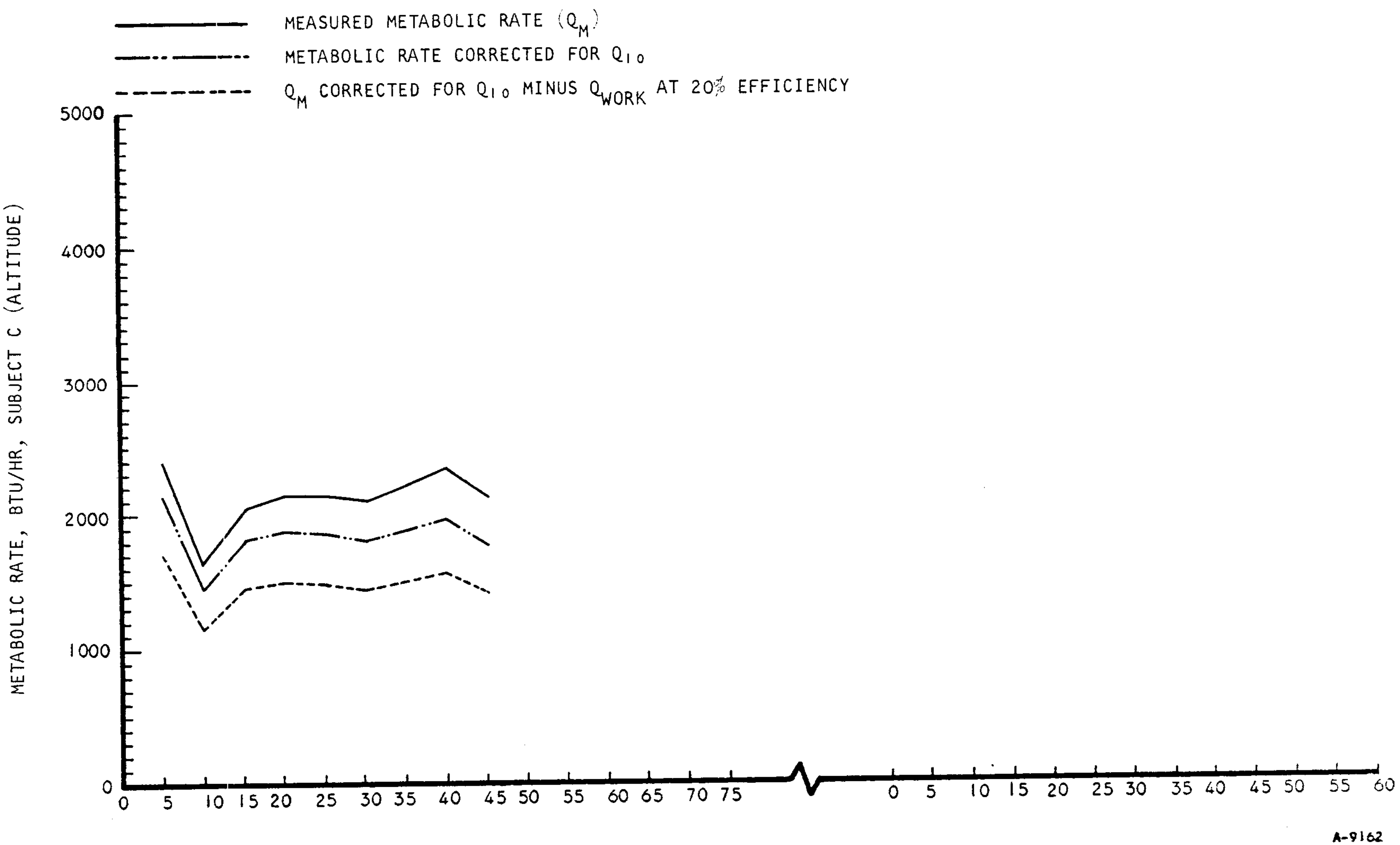


Figure 21. Metabolic Rate, Subject C (Altitude)

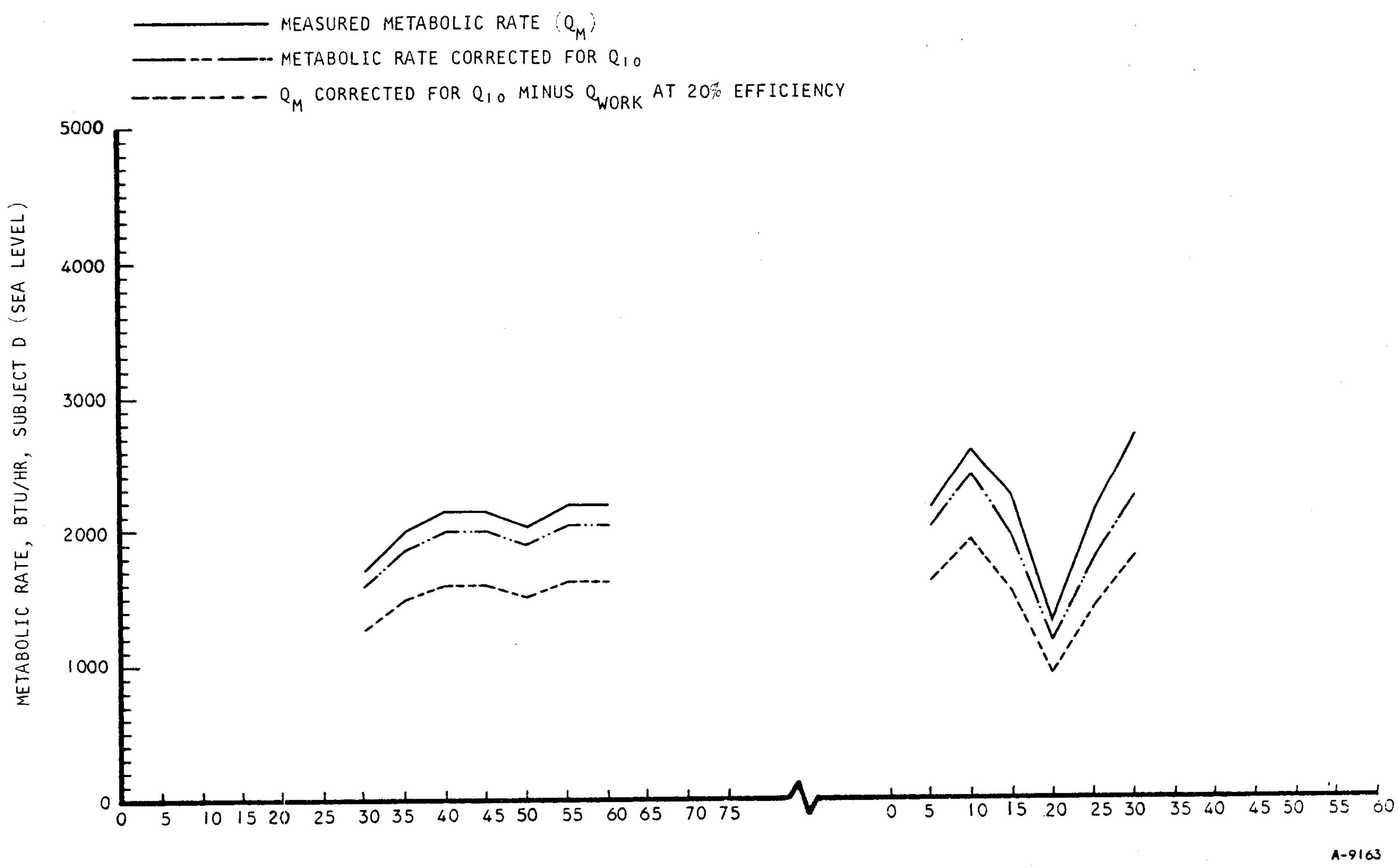


Figure 22. Metabolic Rate, Subject D (Sea Level)

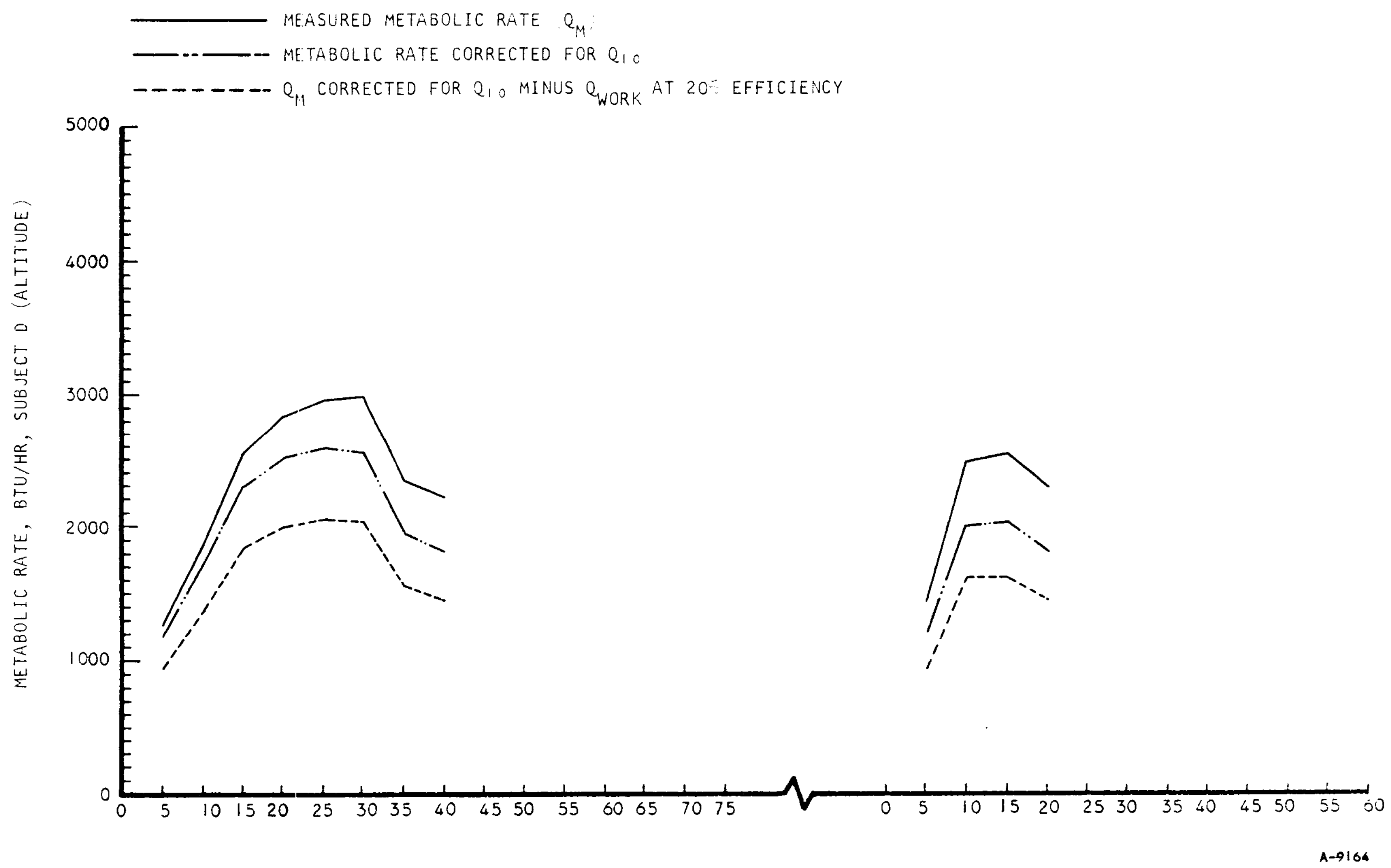


Figure 23. Metabolic Rate, Subject D (Altitude)

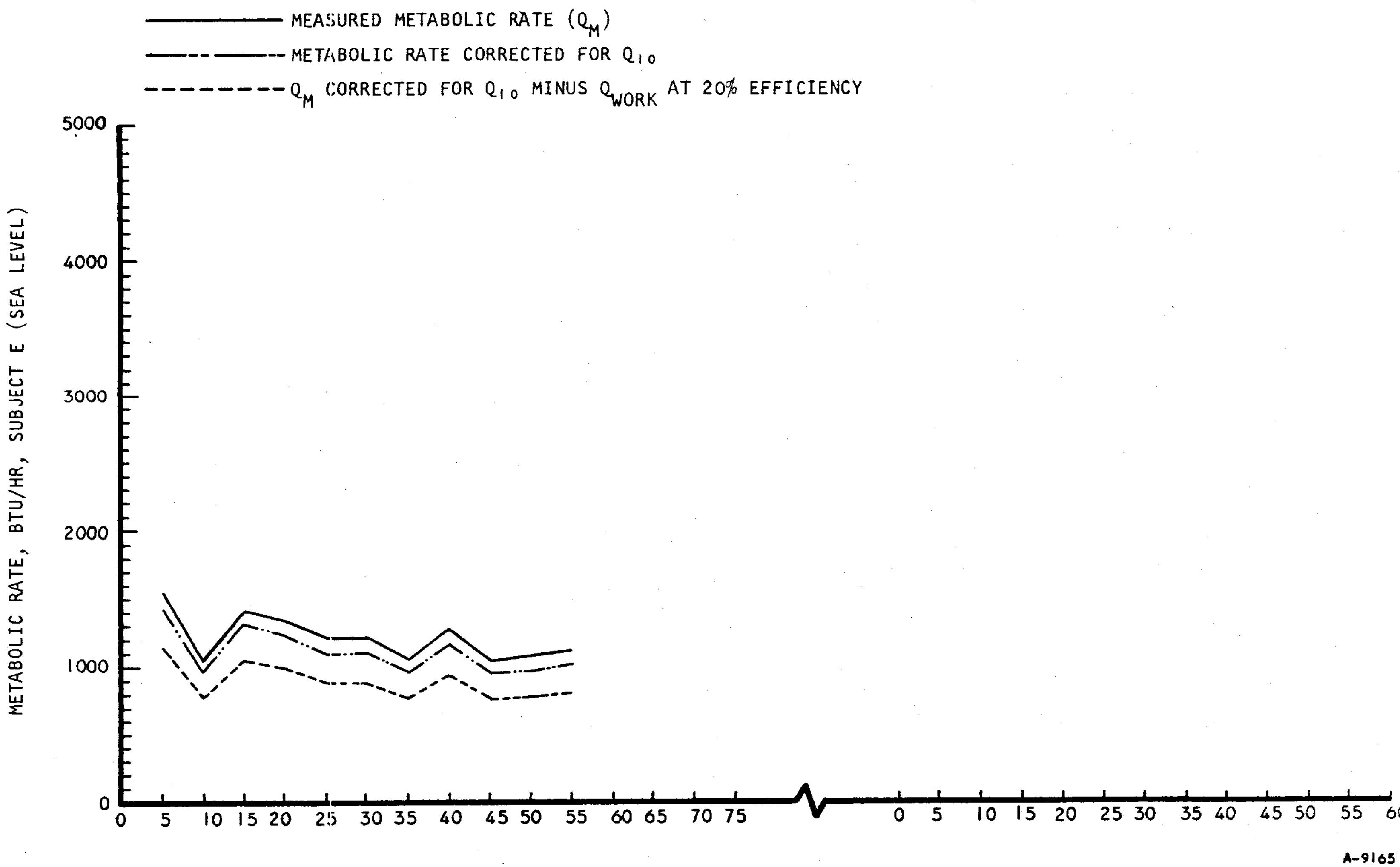


Figure 24. Metabolic Rate, Subject E (Sea Level)

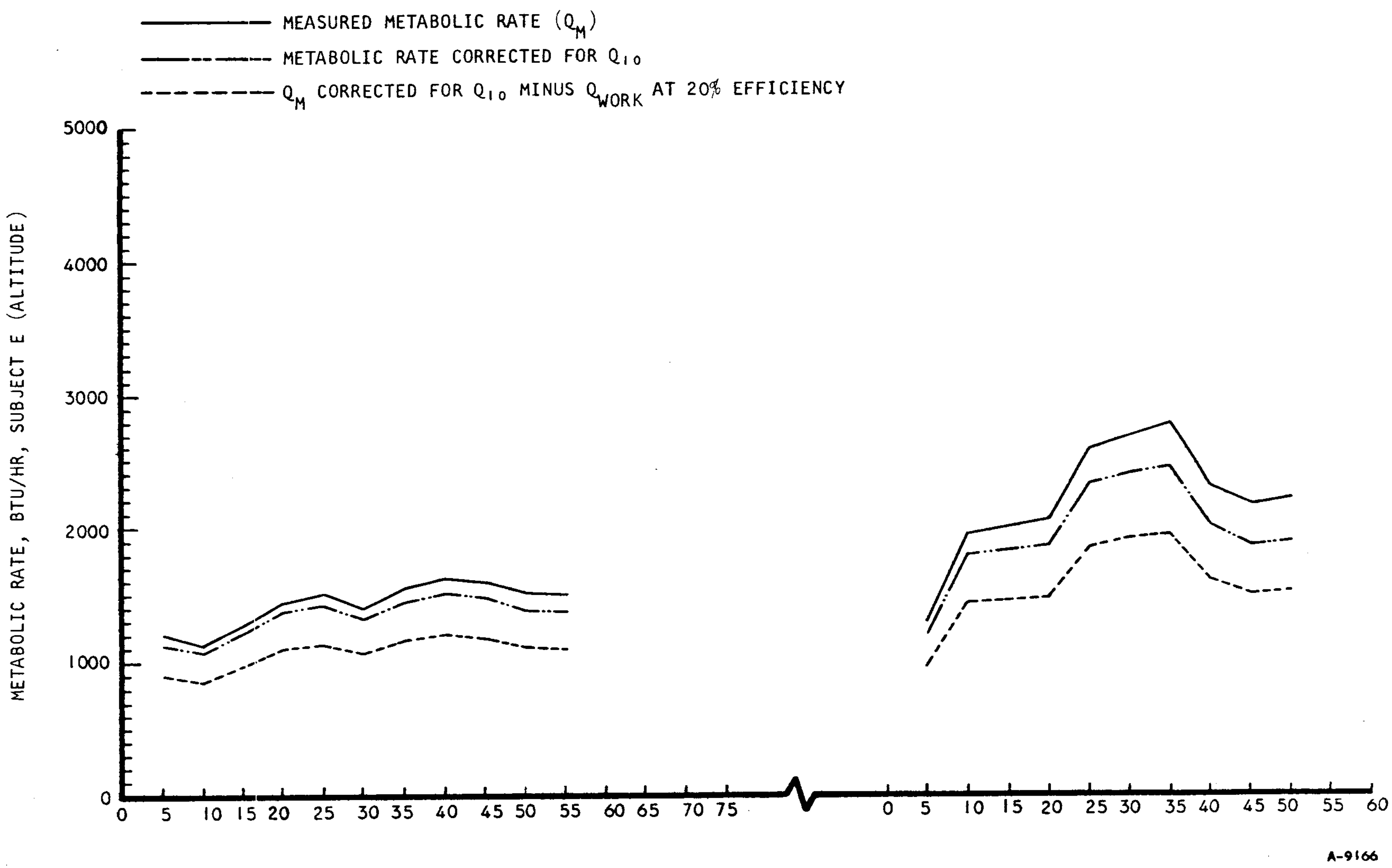


Figure 25. Metabolic Rate, Subject E (Altitude)

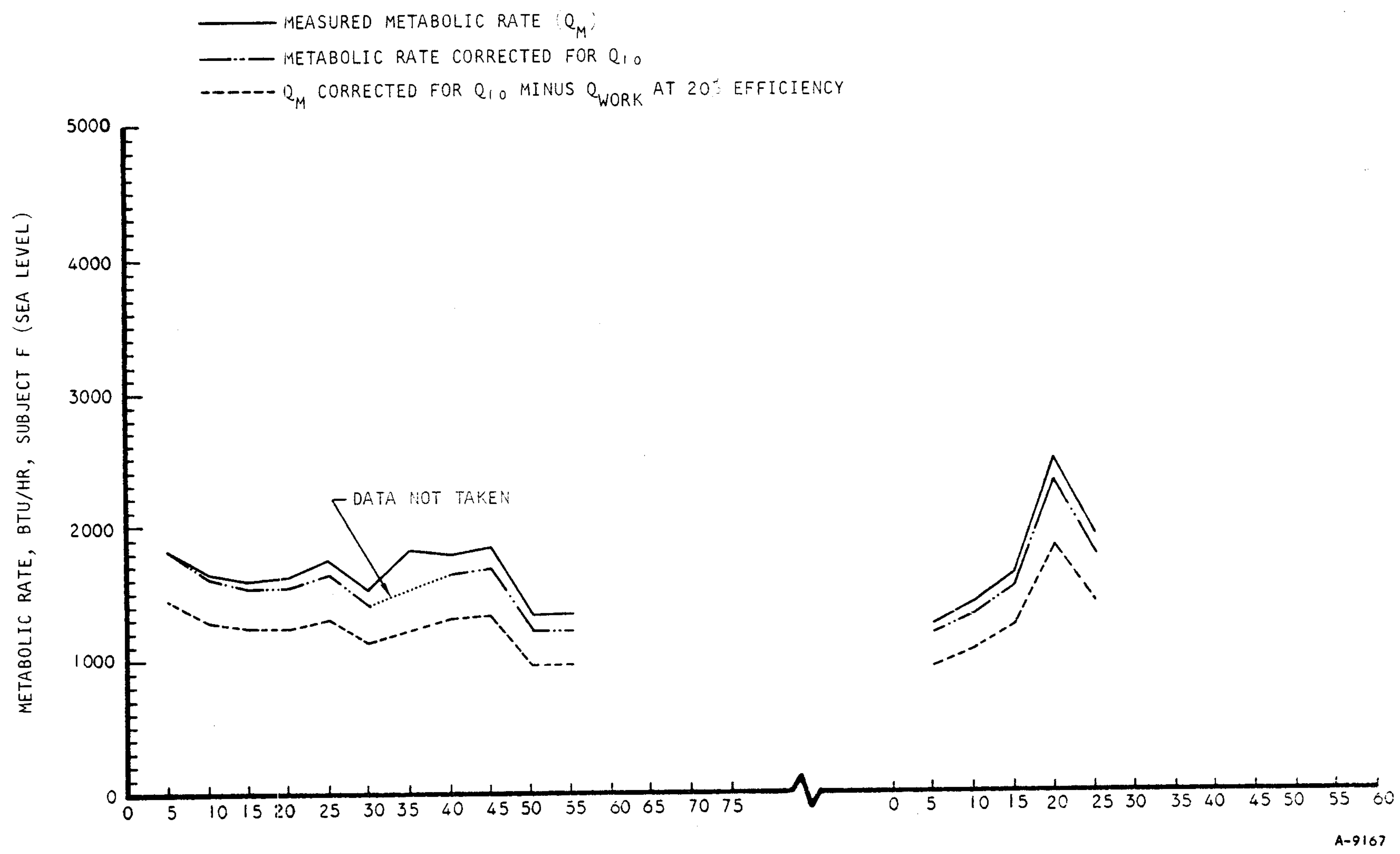


Figure 26. Metabolic Rate, Subject F (Sea Level)

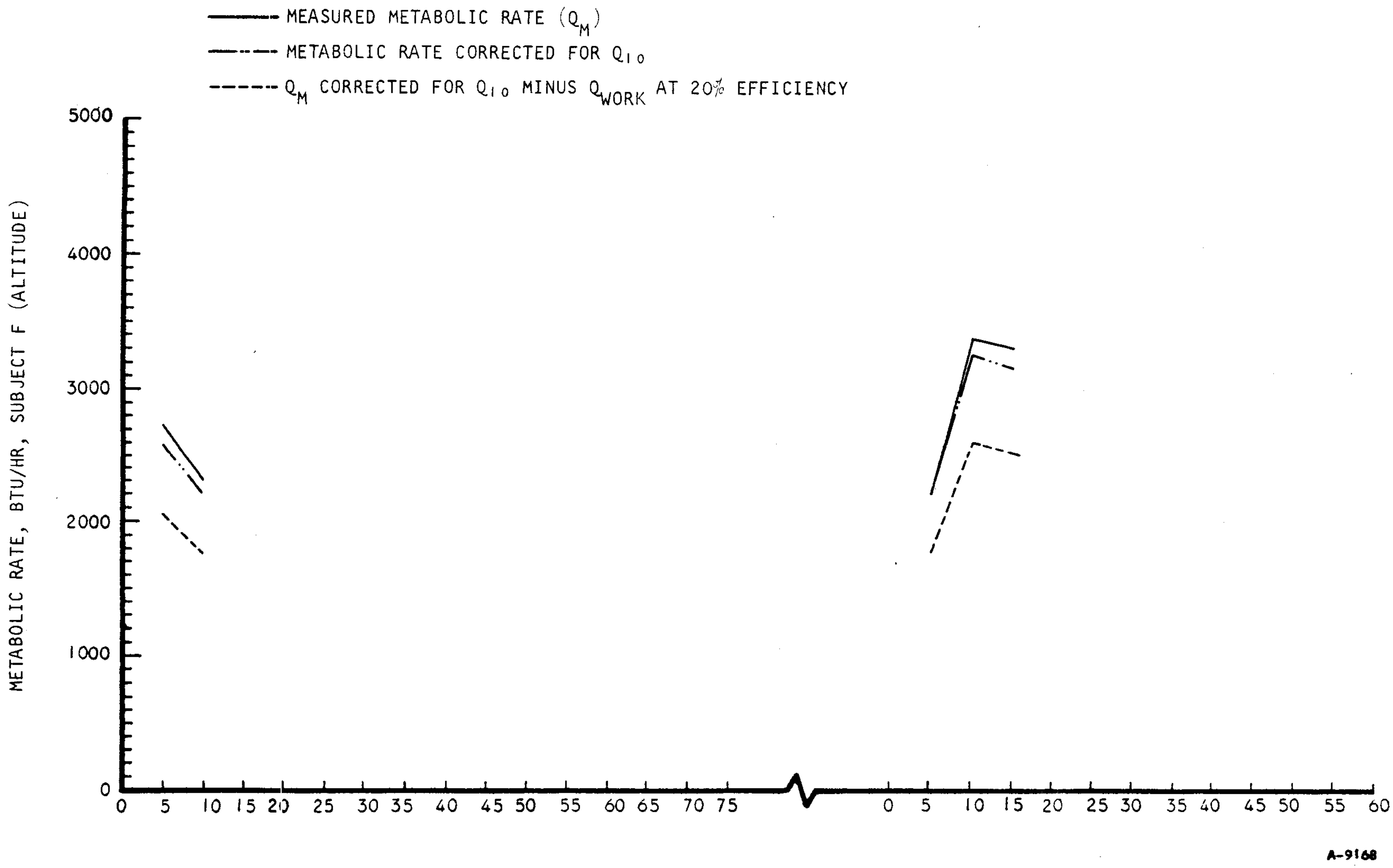


Figure 27. Metabolic Rate, Subject F (Altitude)

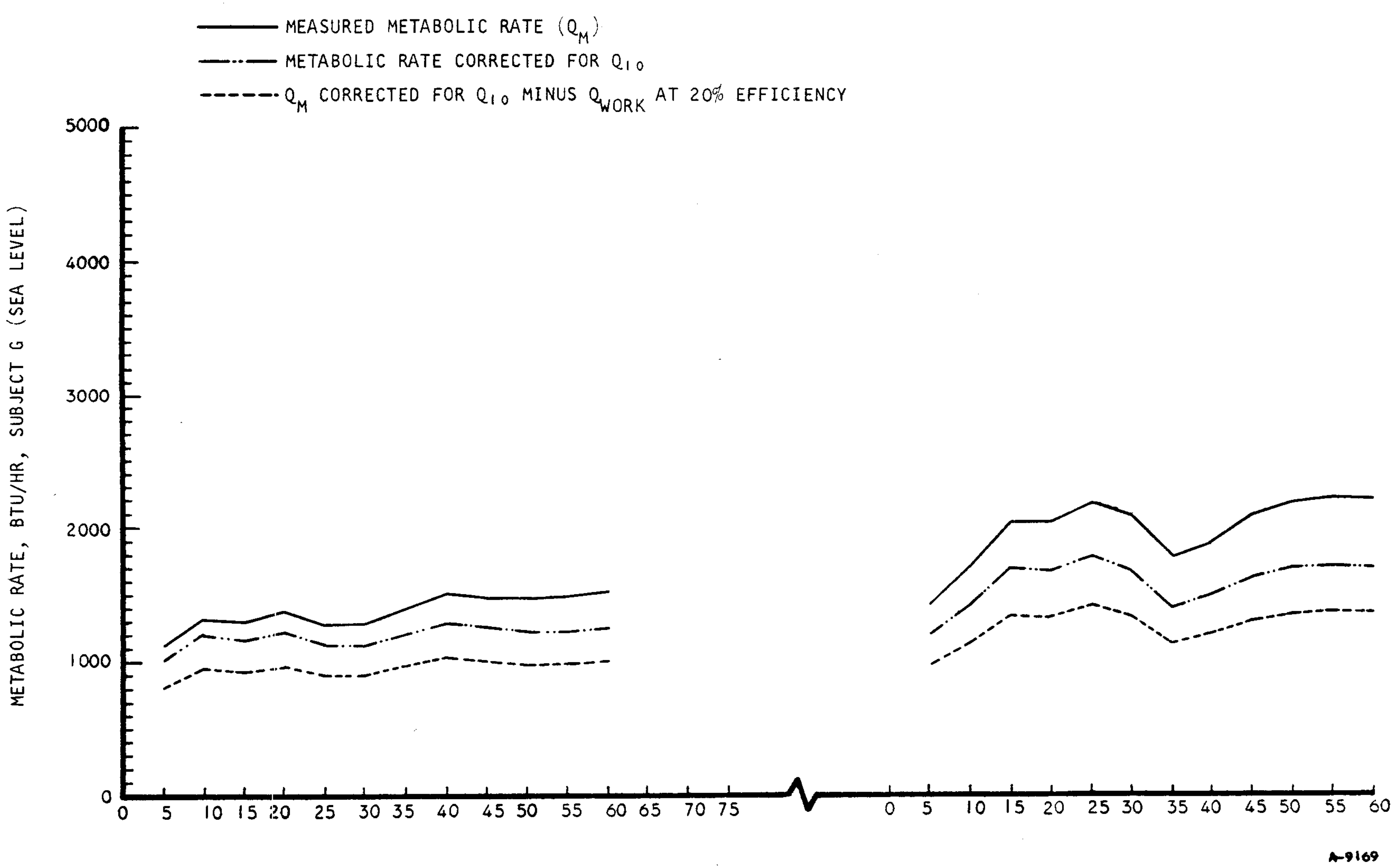


Figure 28. Metabolic Rate, Subject G (Sea Level)

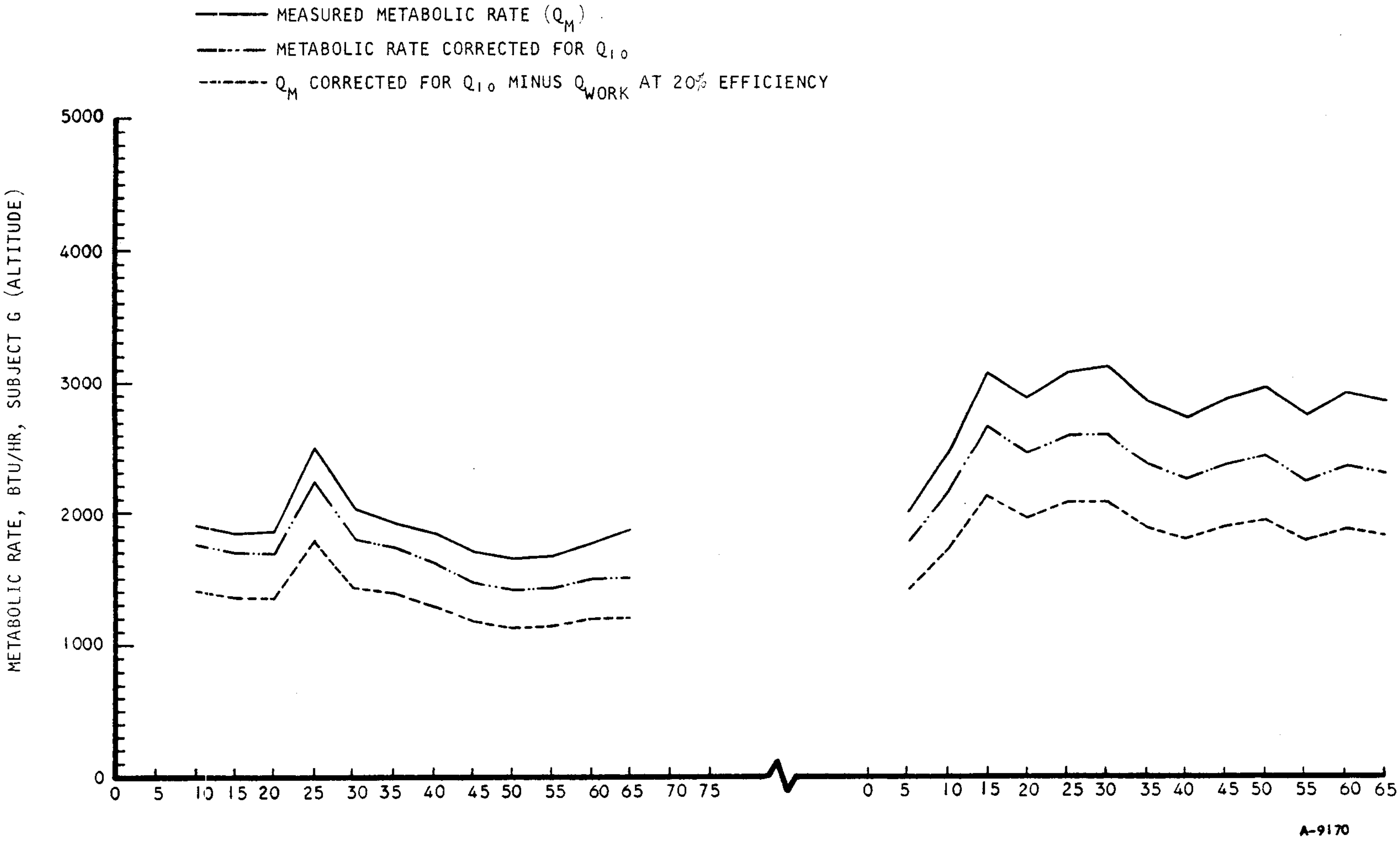


Figure 29. Metabolic Rate, Subject G (Altitude)

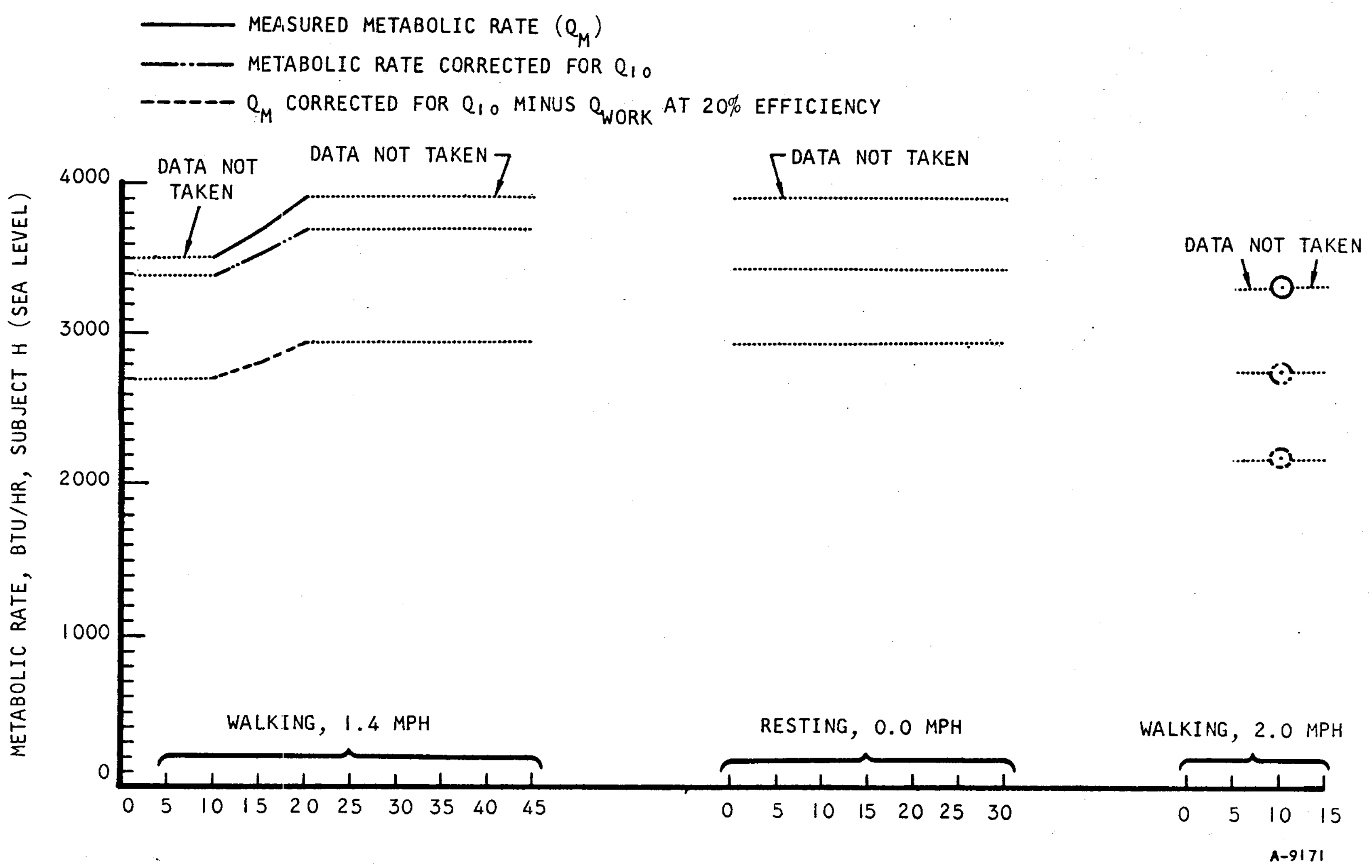


Figure 30. Metabolic Rate, Subject H (Sea Level)

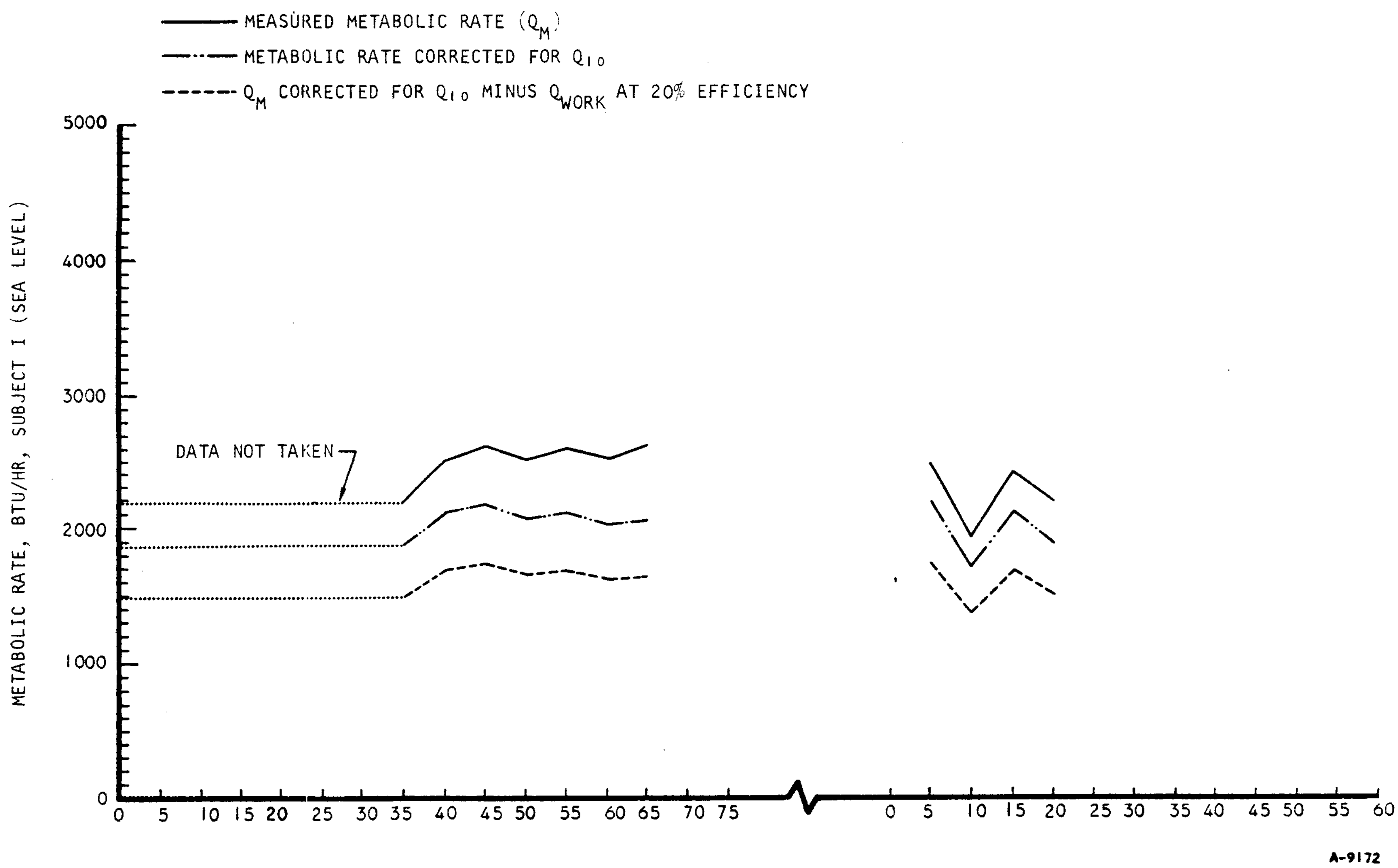


Figure 31. Metabolic Rate, Subject I (Sea Level)

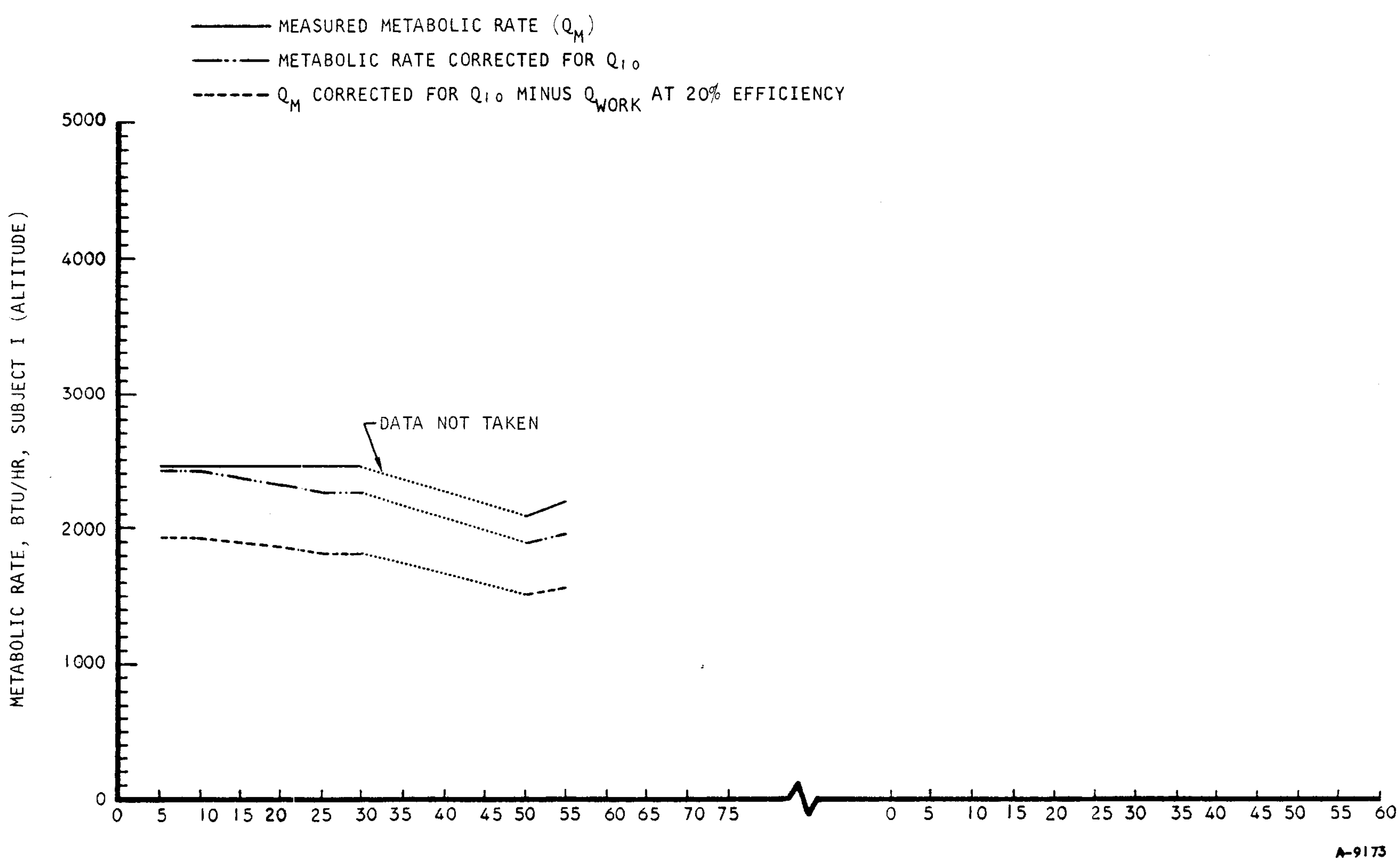


Figure 32. Metabolic Rate, Subject I (Altitude)

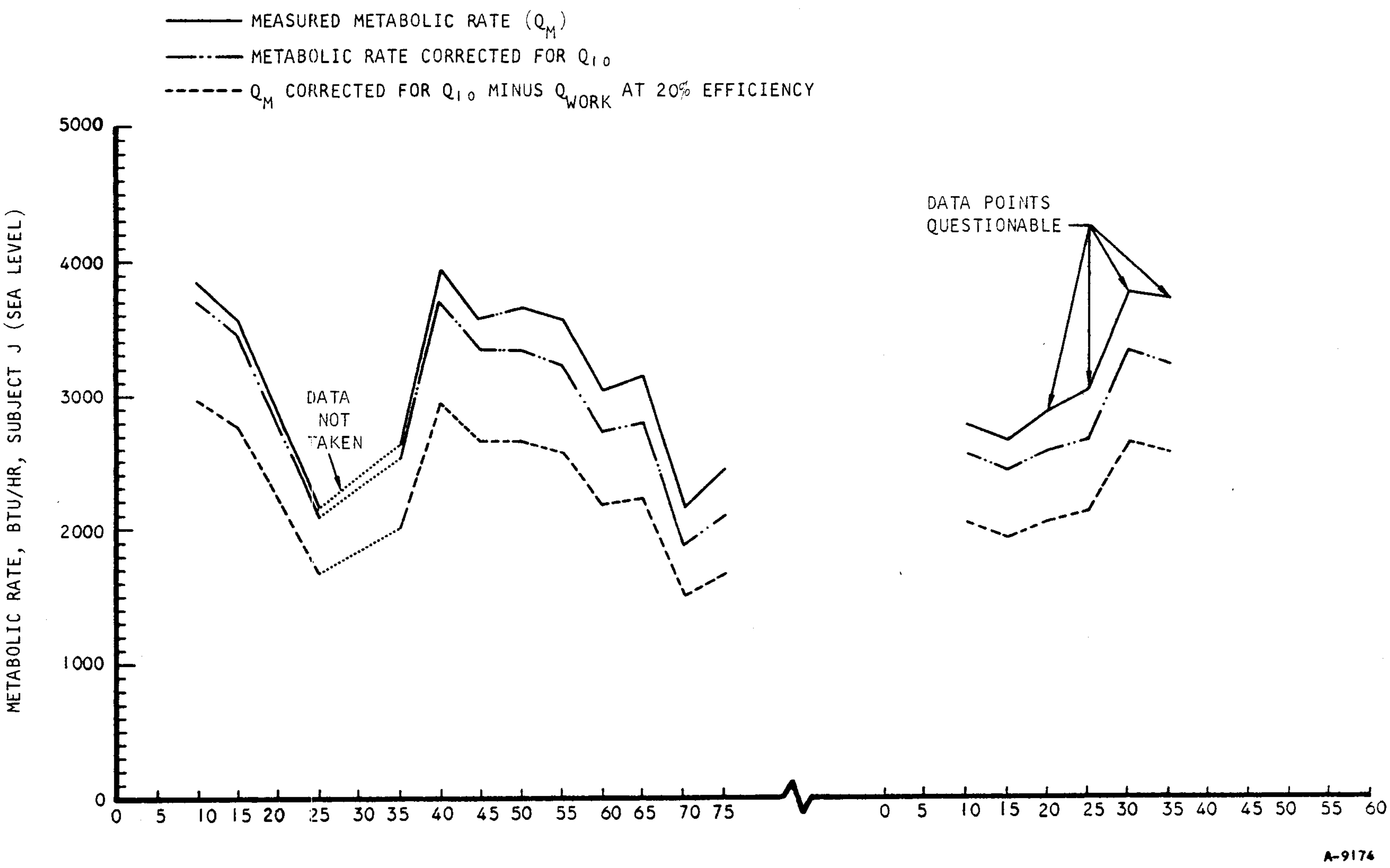


Figure 33. Metabolic Rate, Subject J (Sea Level)

VENTILATION HEAT REMOVAL AT SEA LEVEL

The figures in this section (Figures 34 through 43) present the data obtained on heat removal from the pressure suit. Curves are presented for total heat removal, latent heat removal, sensible heat removal, and net heat removal. The net heat removed from the suit is that portion of the total heat from metabolic sources and is equivalent to the total heat less the heat from pumping losses. This latter source of heat varied from 101 to 117 Btu/hr.

The curves shown at left in each figure are for work rates of 1.4 mph, and those at right are for 2.0 mph.

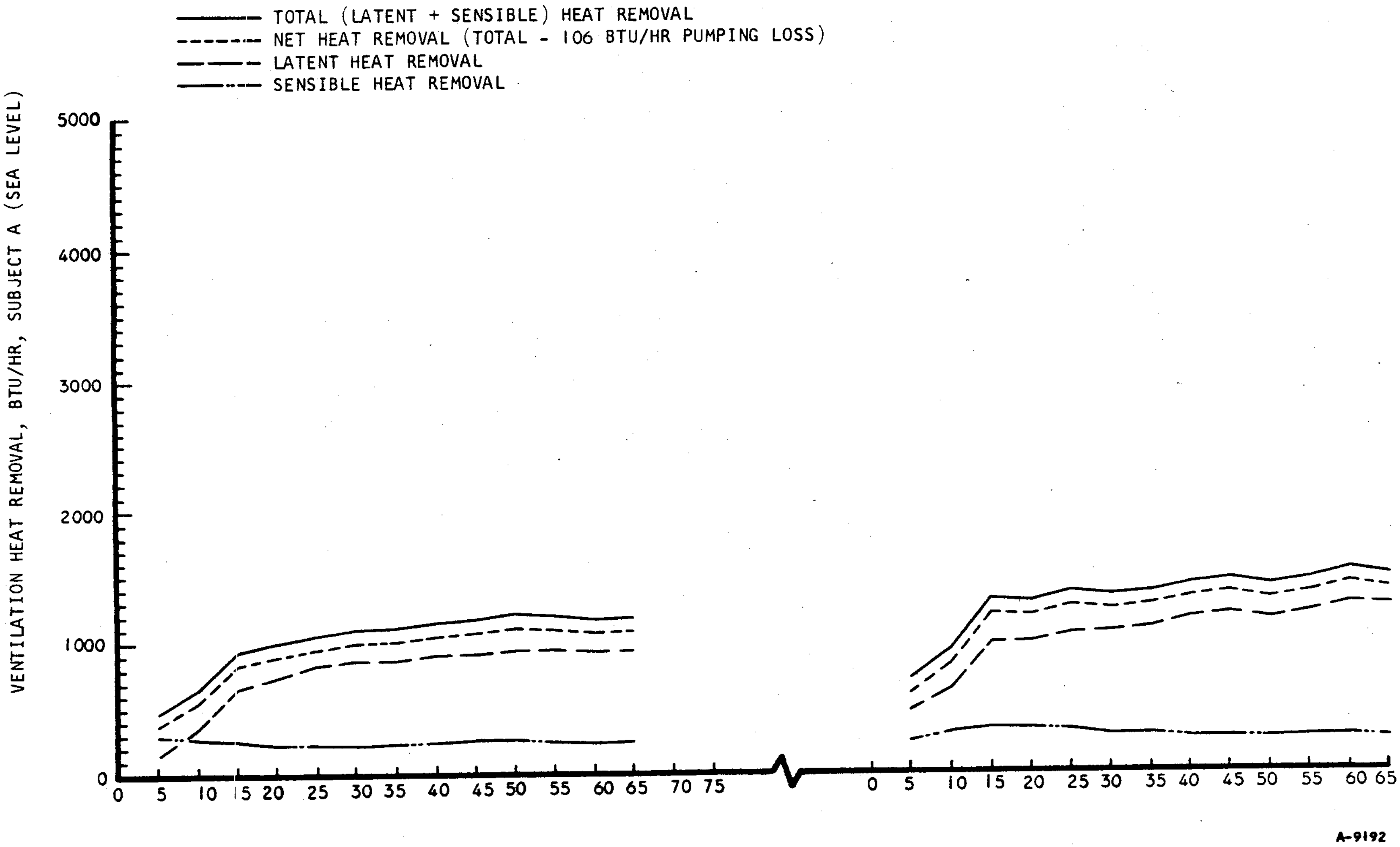


Figure 34. Ventilation Heat Removal, Subject A (Sea Level)

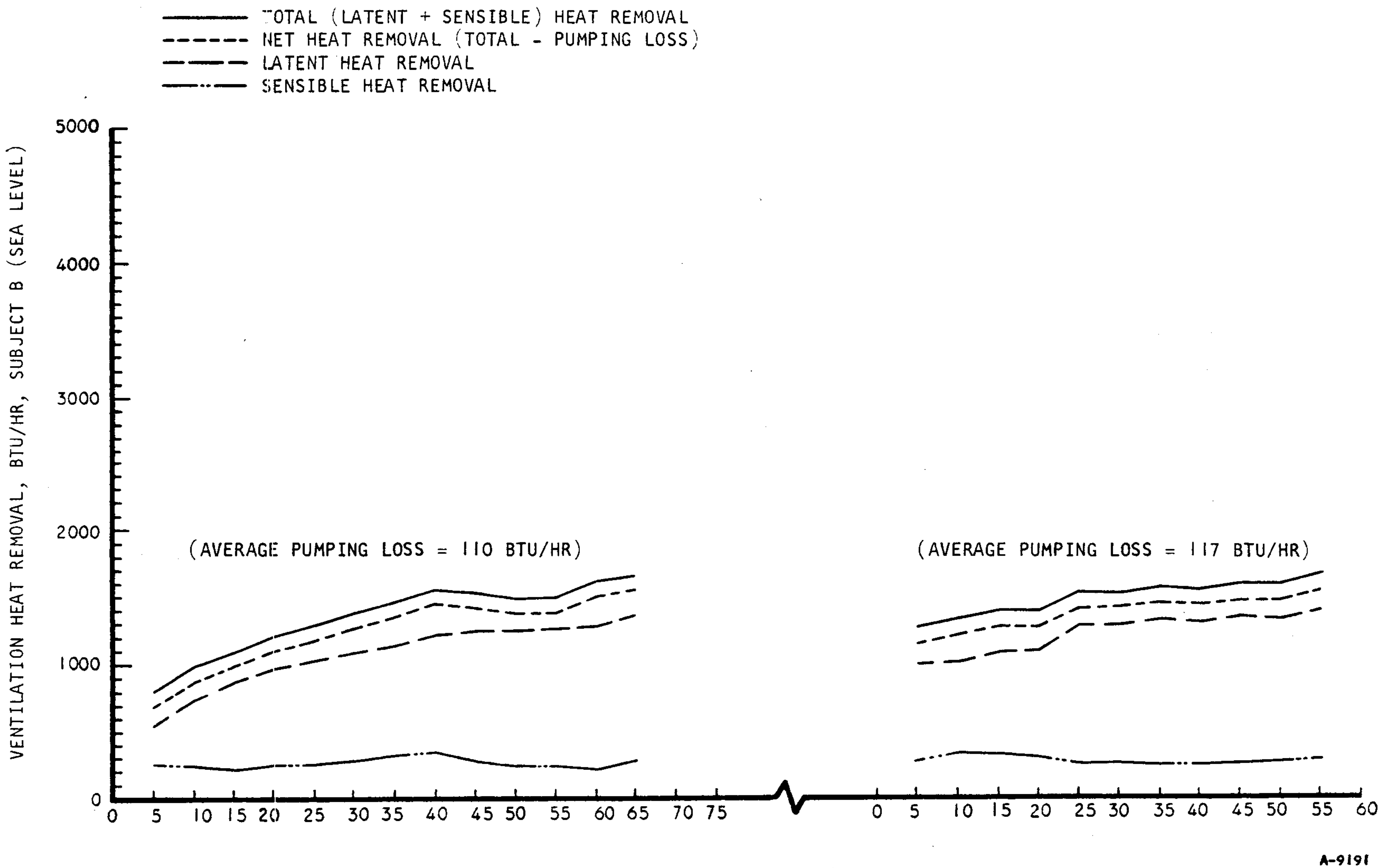


Figure 35. Ventilation Heat Removal, Subject B (Sea Level)

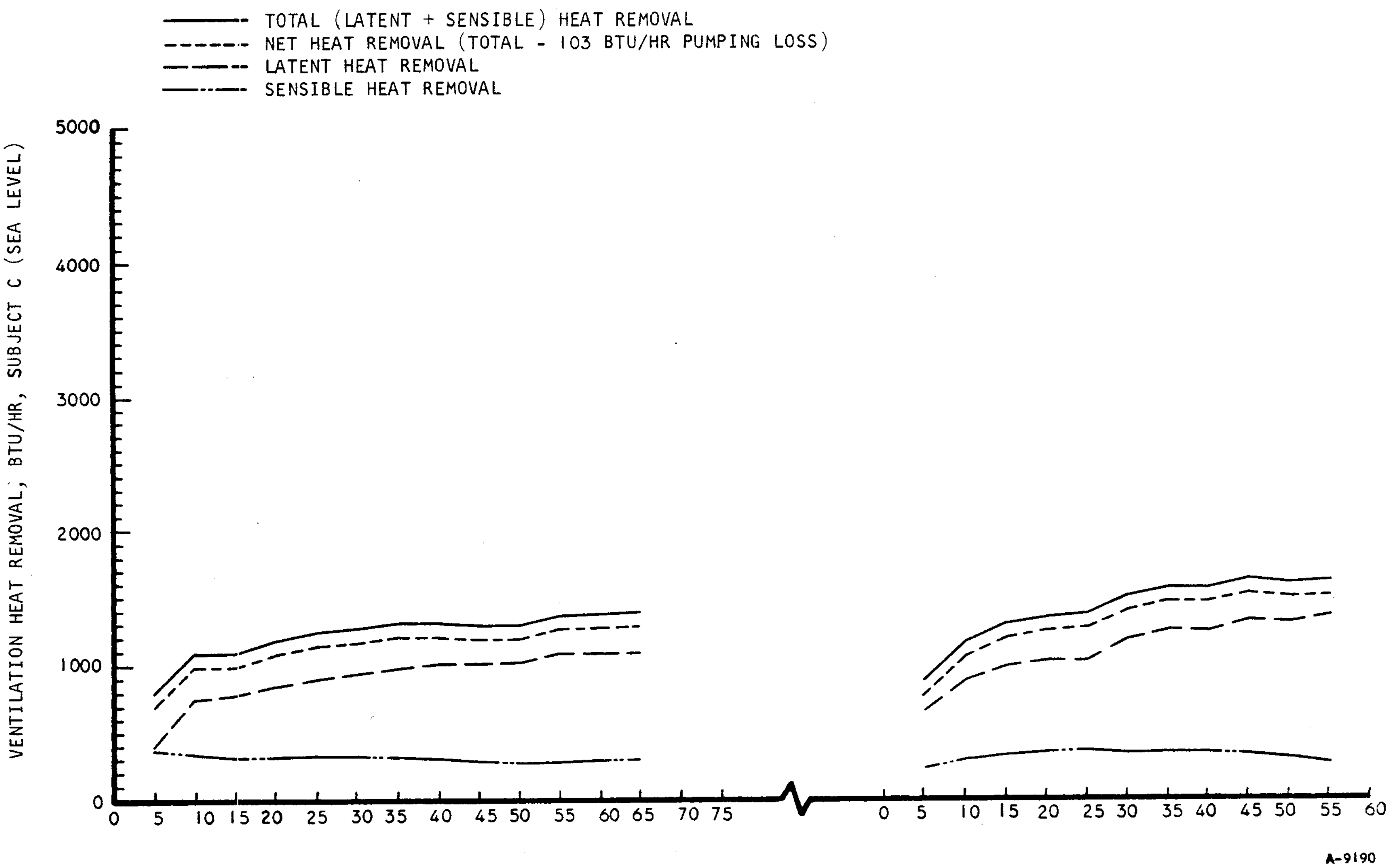


Figure 36. Ventilation Heat Removal, Subject C (Sea Level)

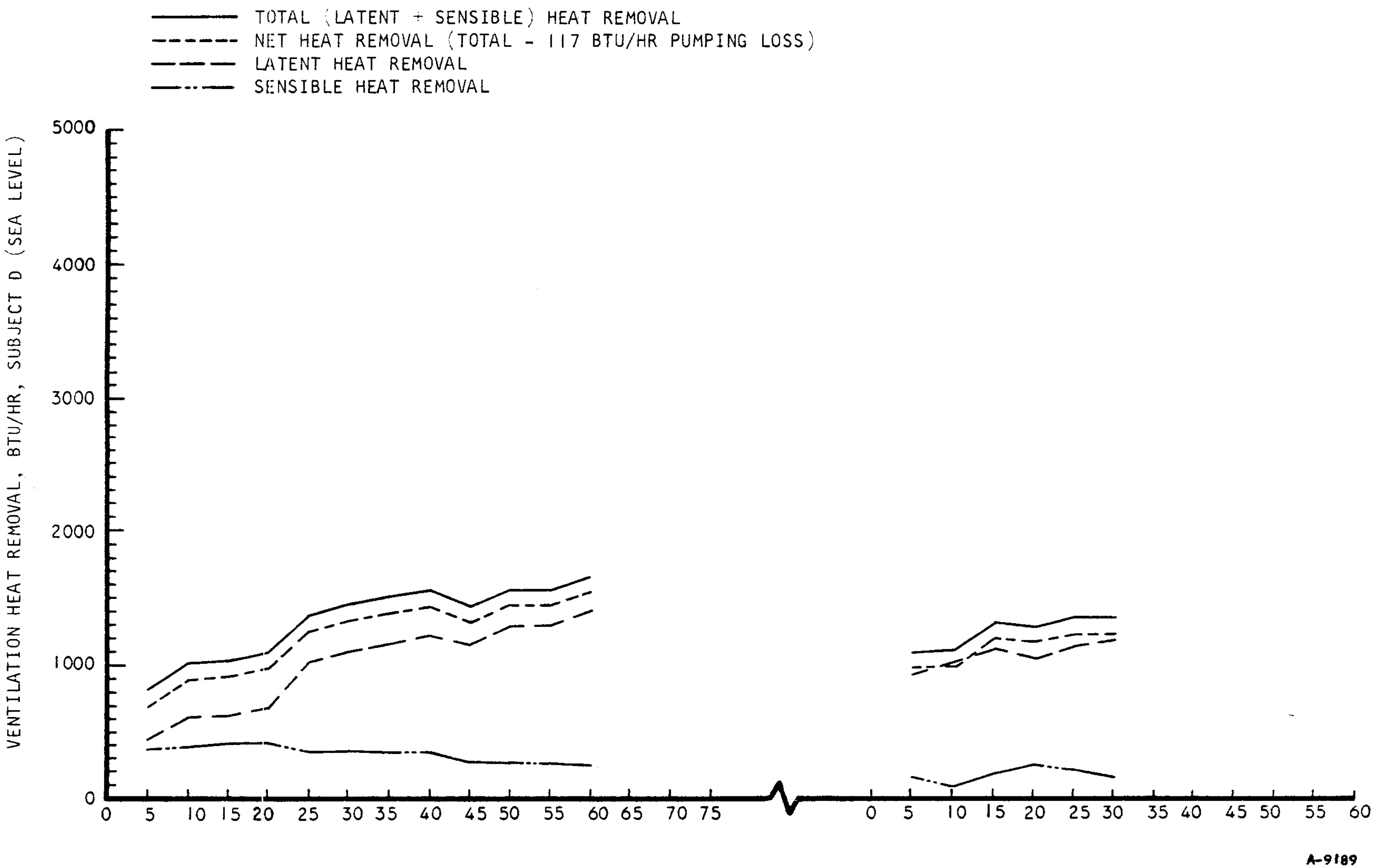


Figure 37. Ventilation Heat Removal, Subject D (Sea Level)

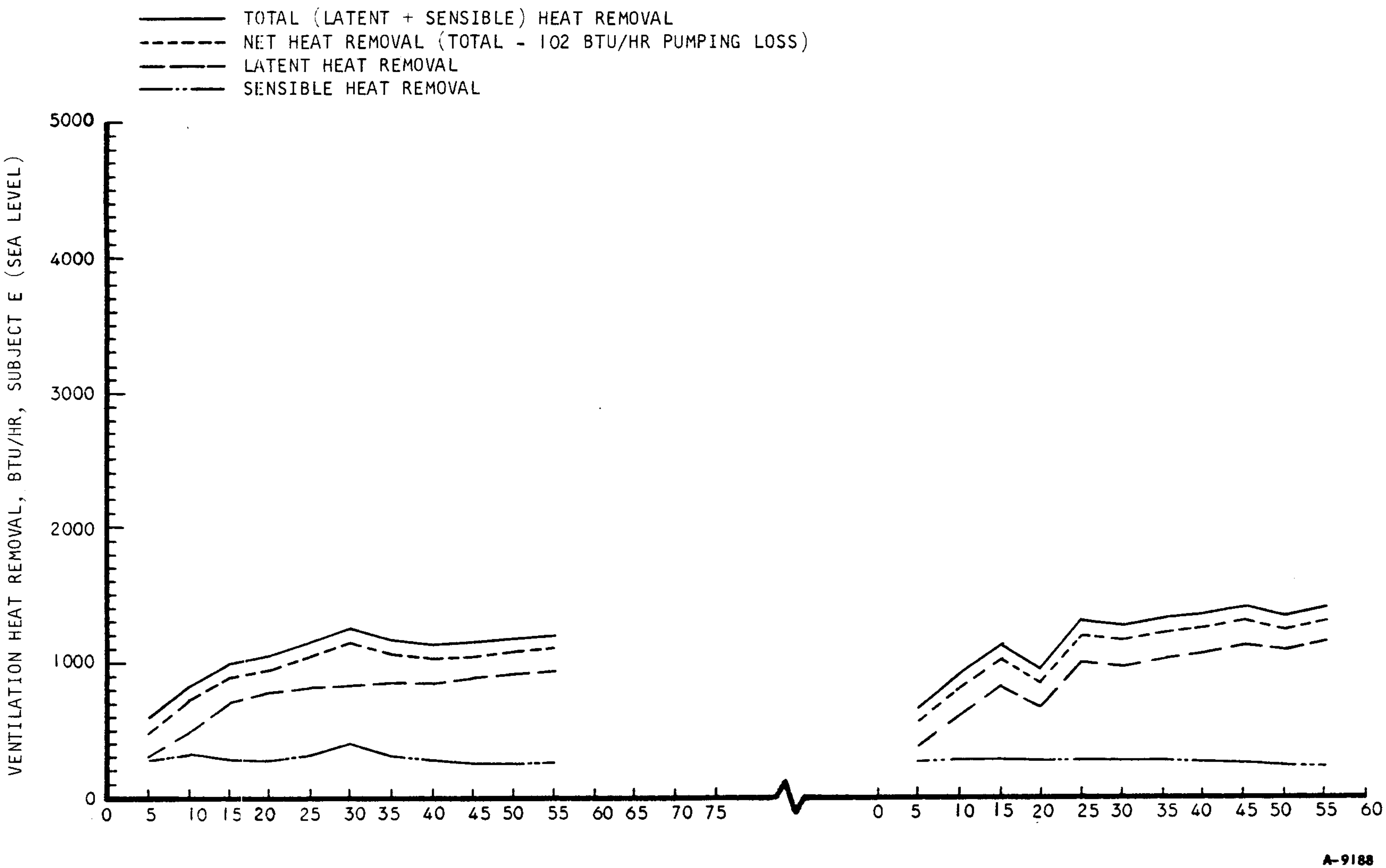


Figure 38. Ventilation Heat Removal, Subject E (Sea Level)

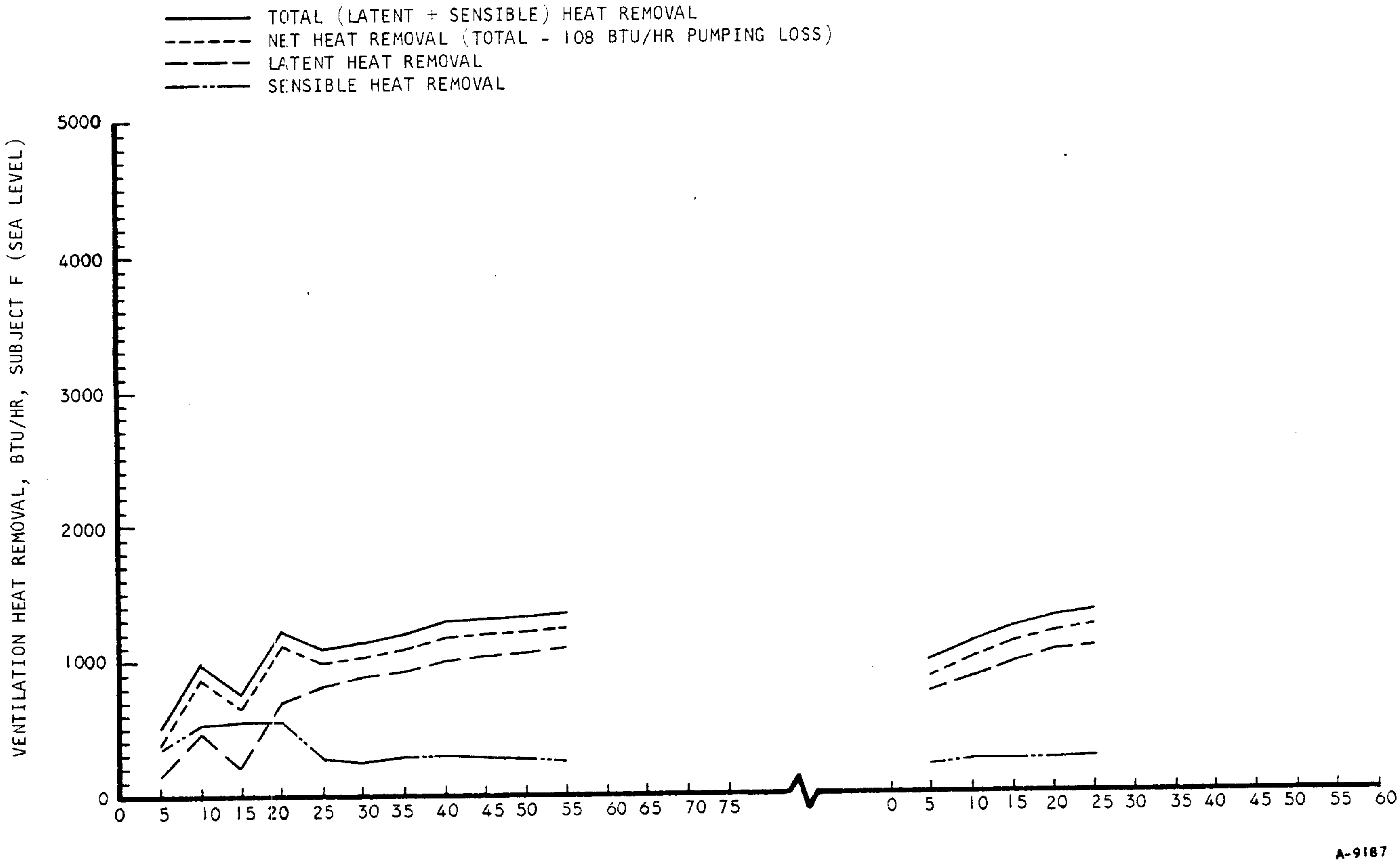


Figure 39. Ventilation Heat Removal, Subject F (Sea Level)

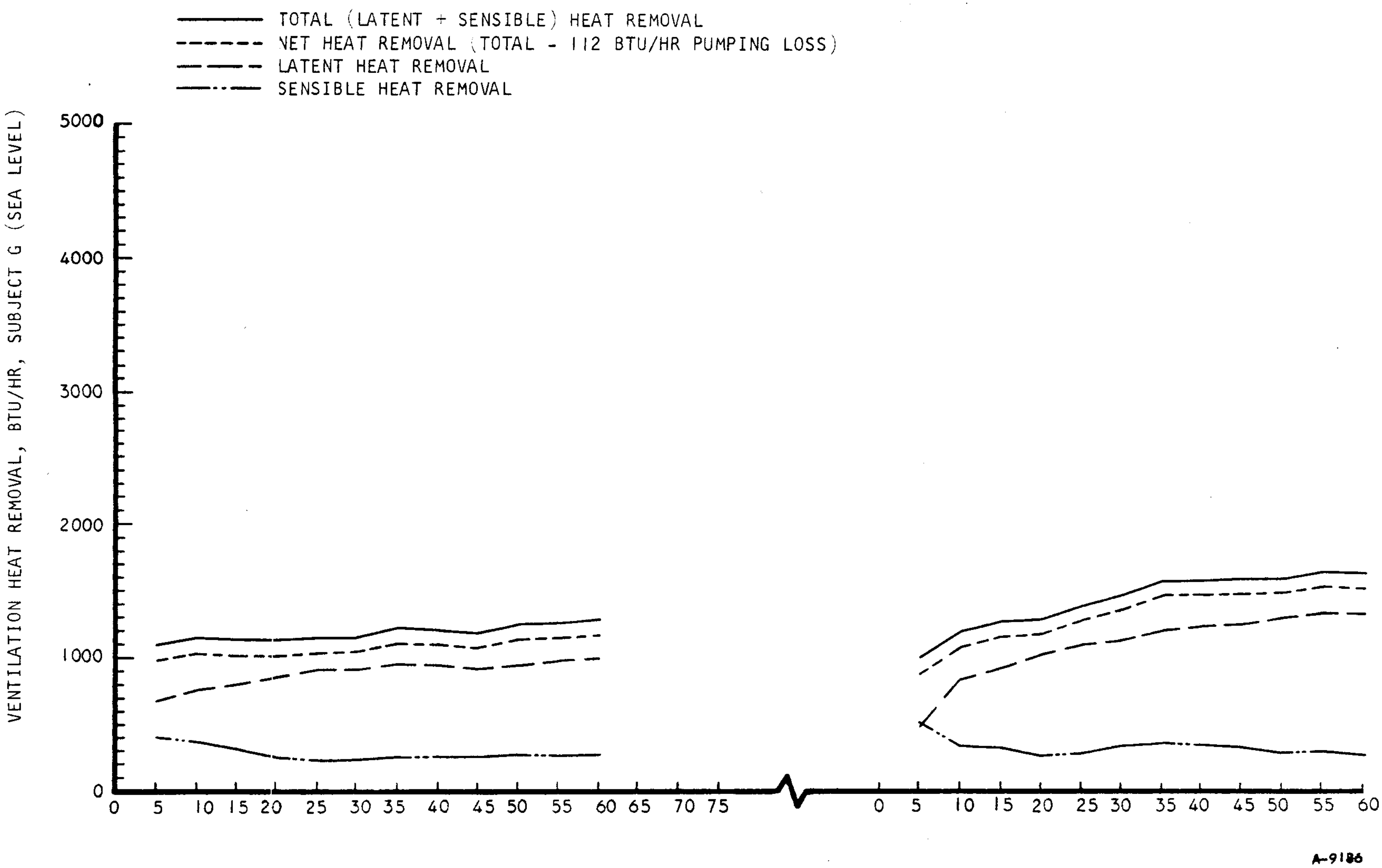


Figure 40. Ventilation Heat Removal, Subject G (Sea Level)

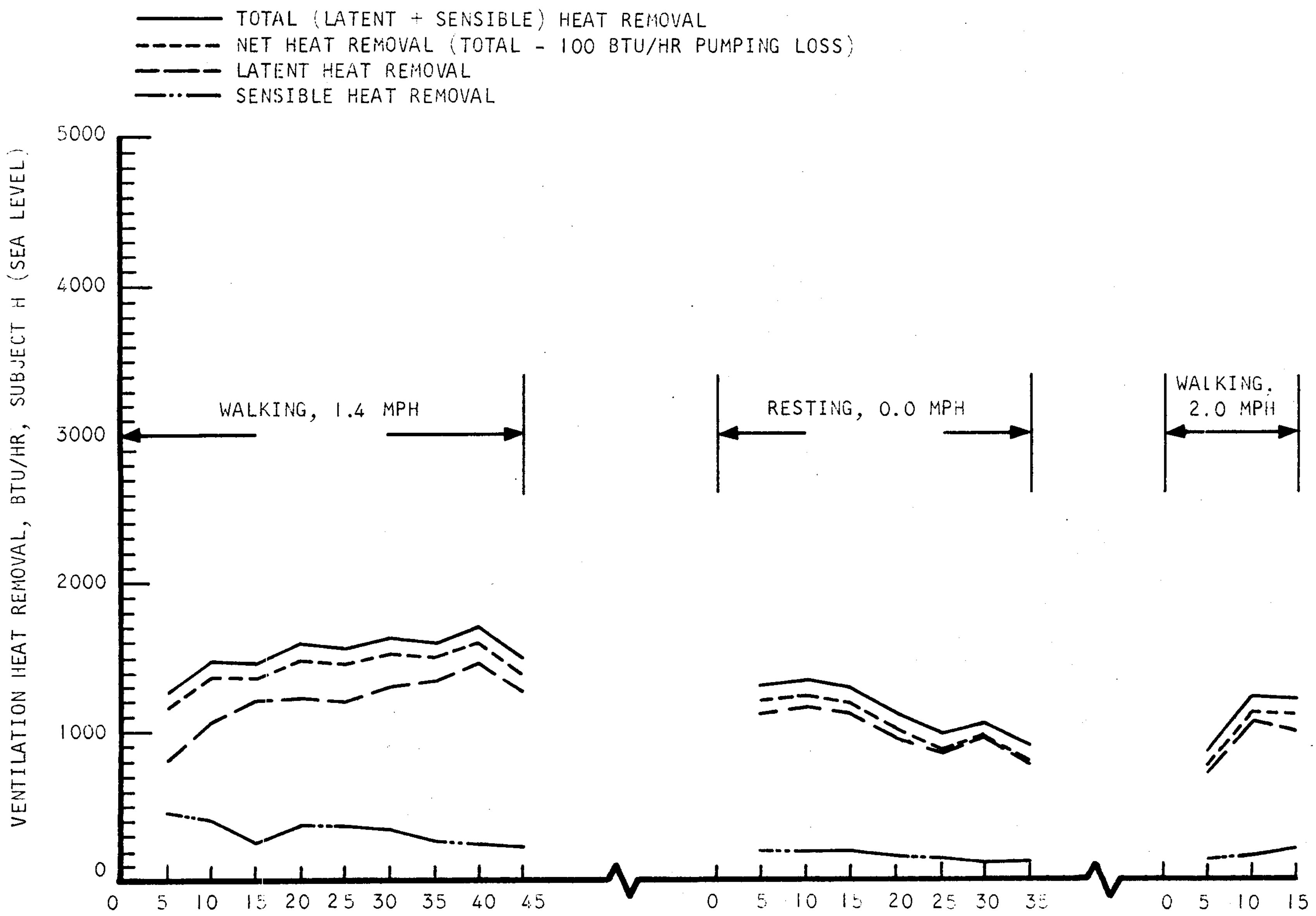


Figure 41. Ventilation Heat Removal, Subject H (Sea Level)

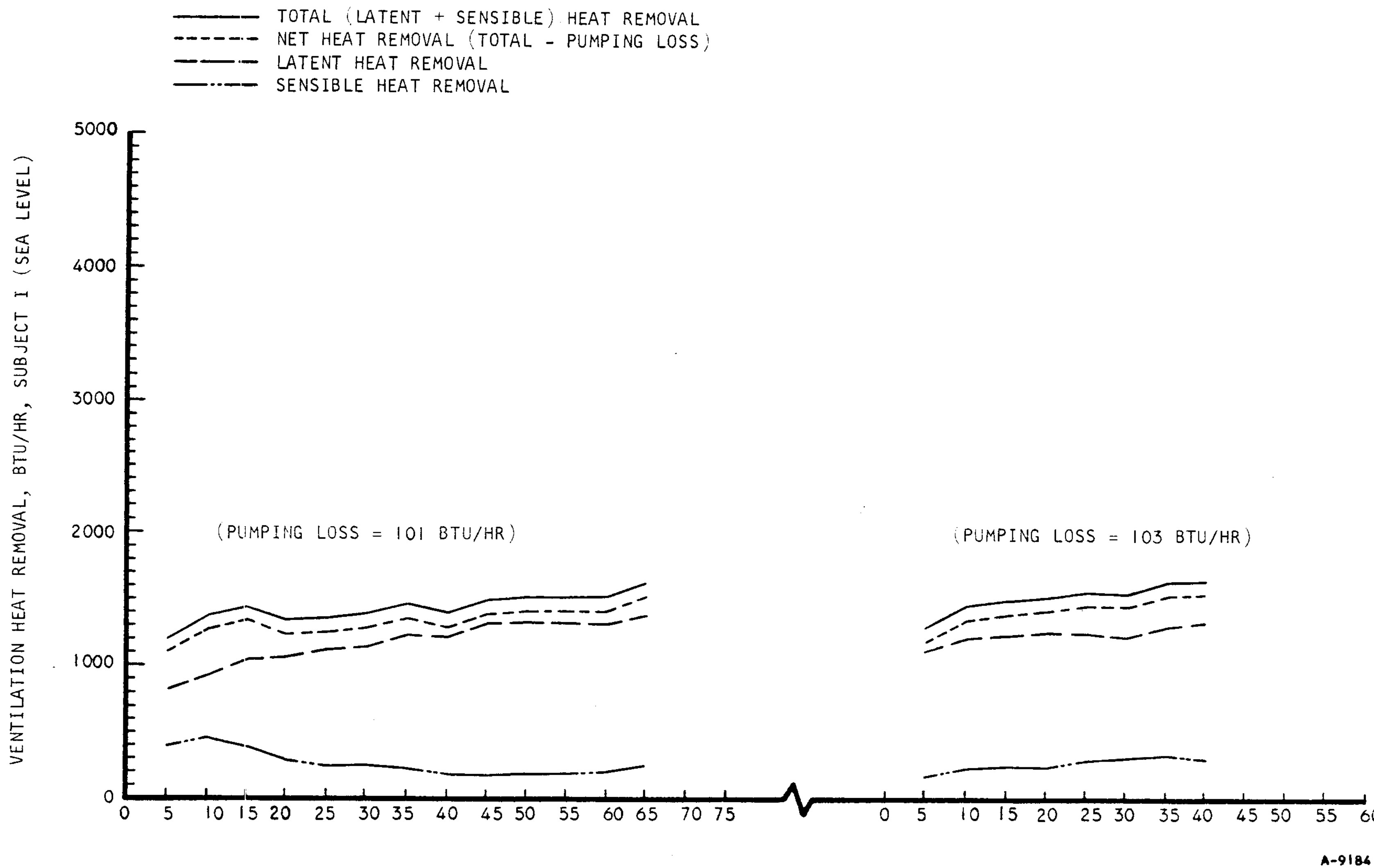


Figure 42. Ventilation Heat Removal, Subject I (Sea Level)

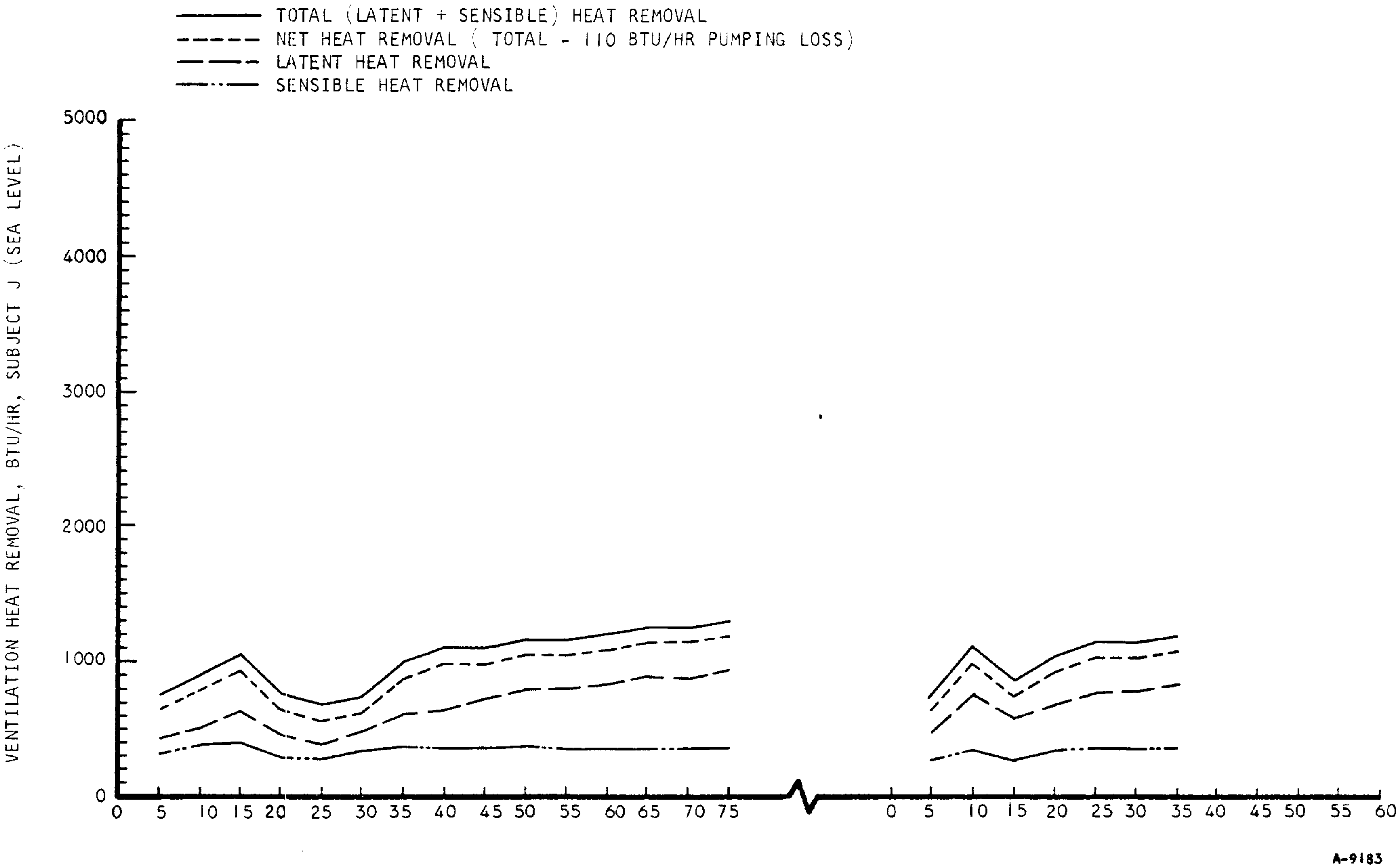


Figure 43. Ventilation Heat Removal, Subject J (Sea Level)

VENTILATION HEAT REMOVAL AT ALTITUDE

Figures 44 through 51 are plots of the heat removal from the pressure suit at altitude. The curves include data for total heat removal, net heat removal, latent heat removal, and sensible heat removal. The curves shown at left and at right in each figure are for 1.4 and 2.0 mph exercise modes, respectively.

The highest rate of heat removal observed for the end-of-run data points was 1597 Btu/hr and 1638 Btu/hr net heat removals, at sea level and altitude, respectively.

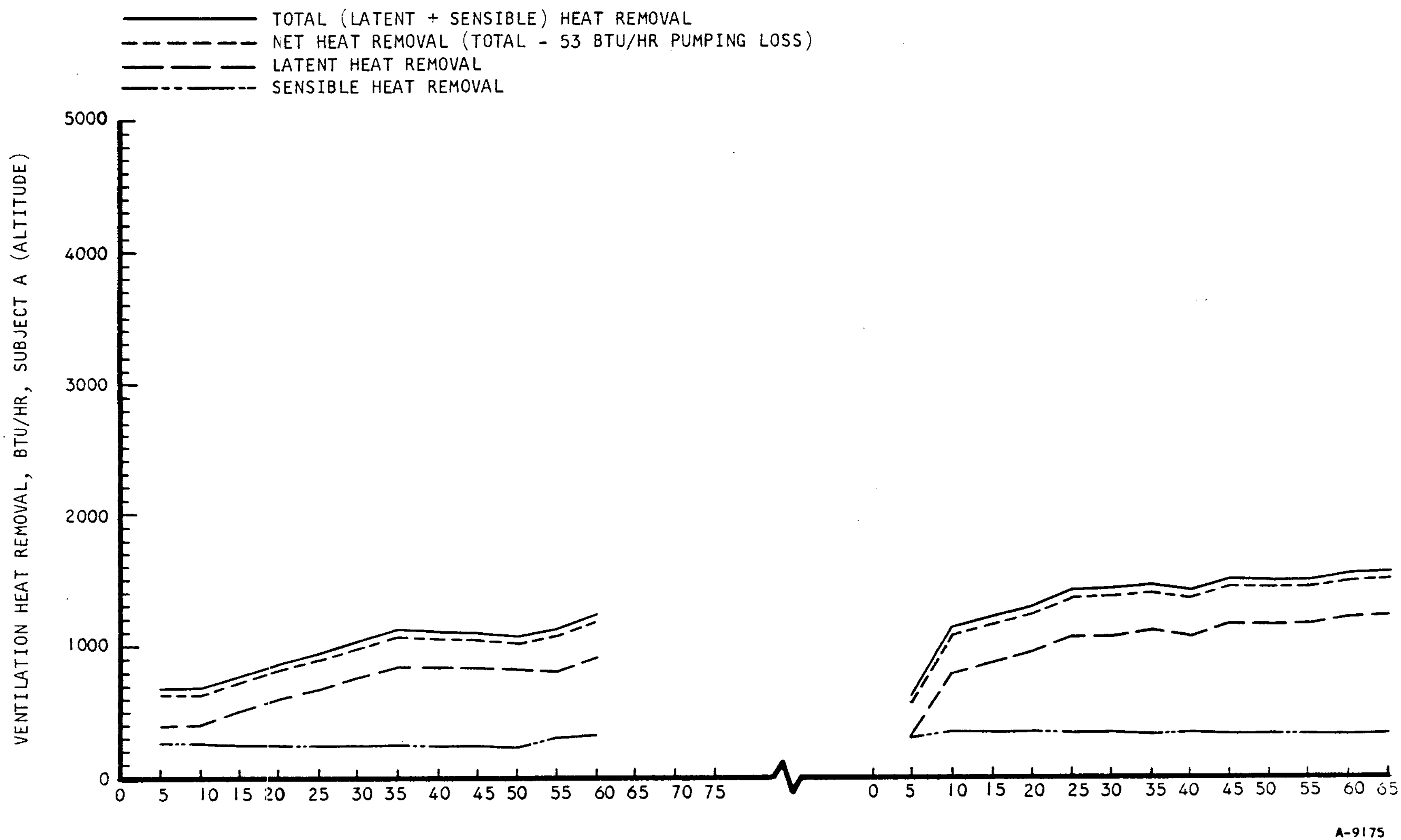


Figure 44. Ventilation Heat Removal, Subject A (Altitude)

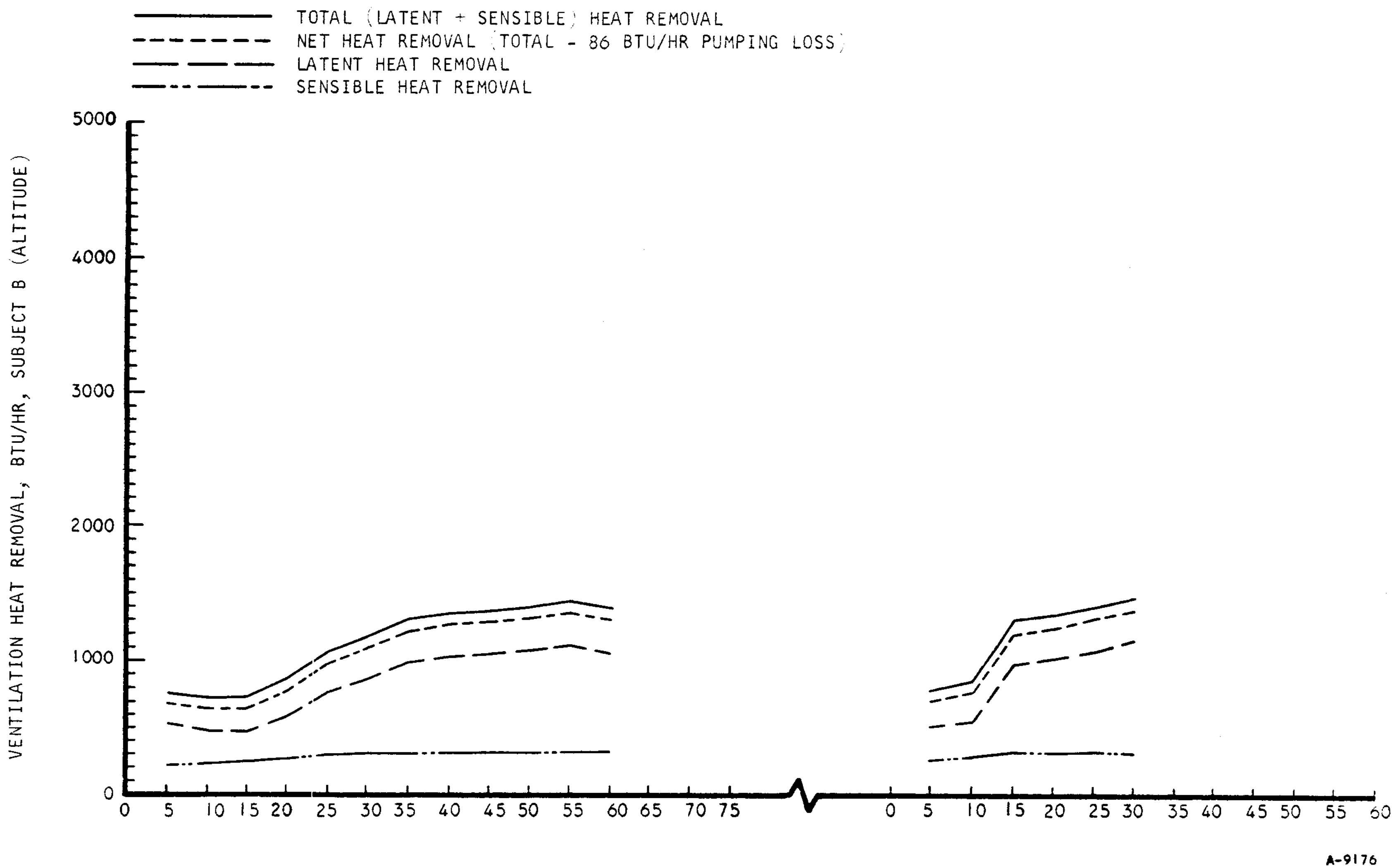


Figure 45. Ventilation Heat Removal, Subject B (Altitude)

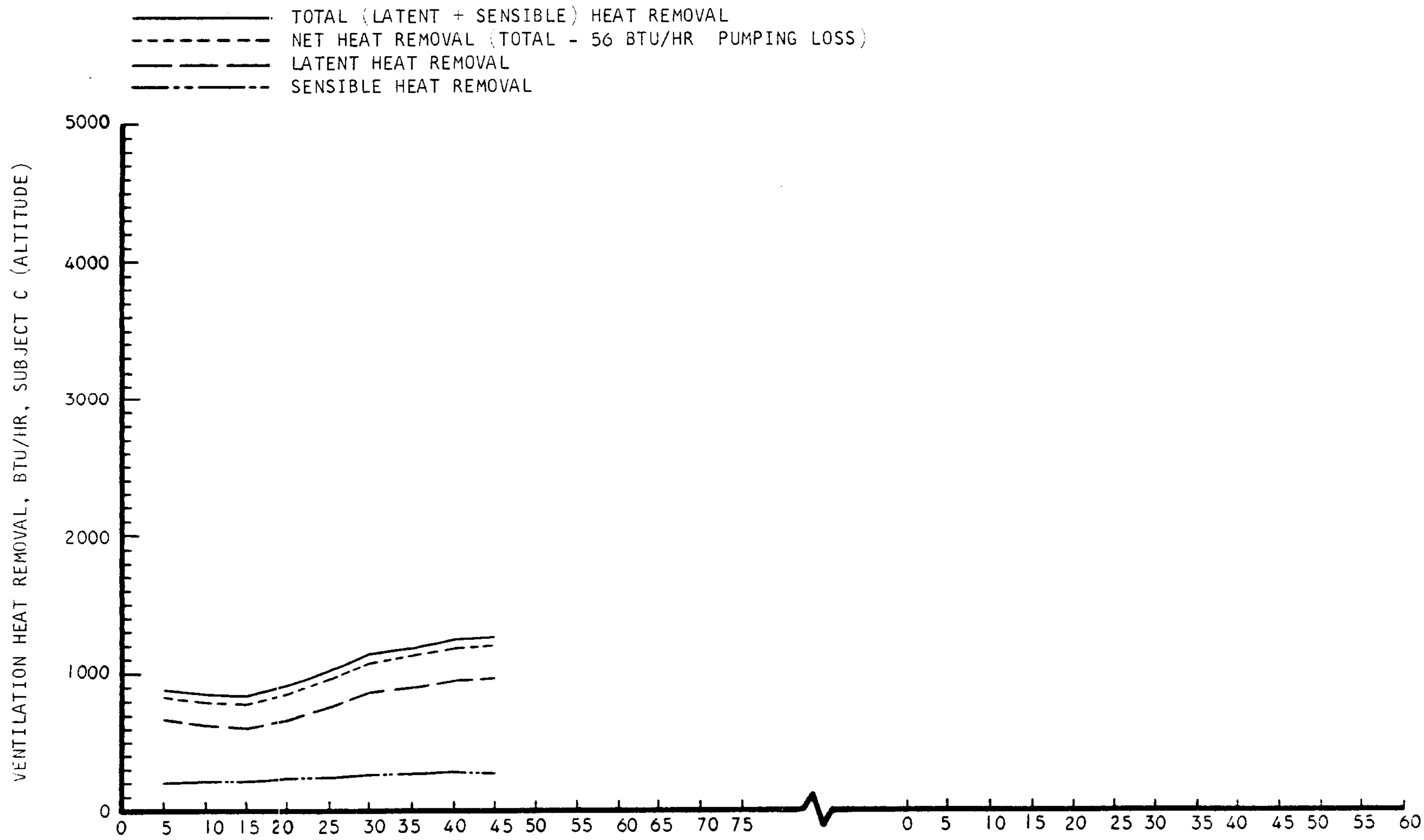


Figure 46. Ventilation Heat Removal, Subject C (Altitude)

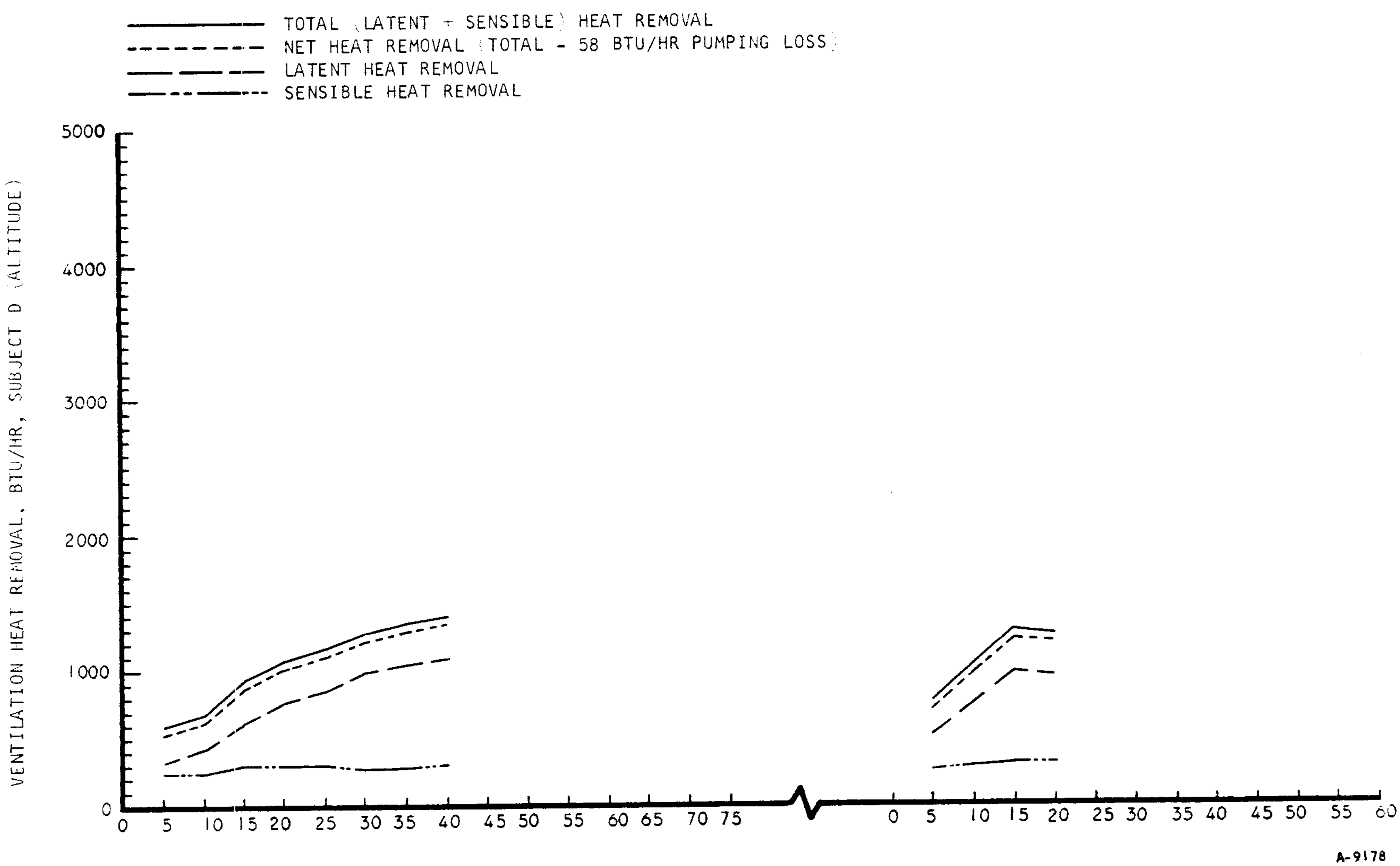


Figure 47. Ventilation Heat Removal, Subject D (Altitude)

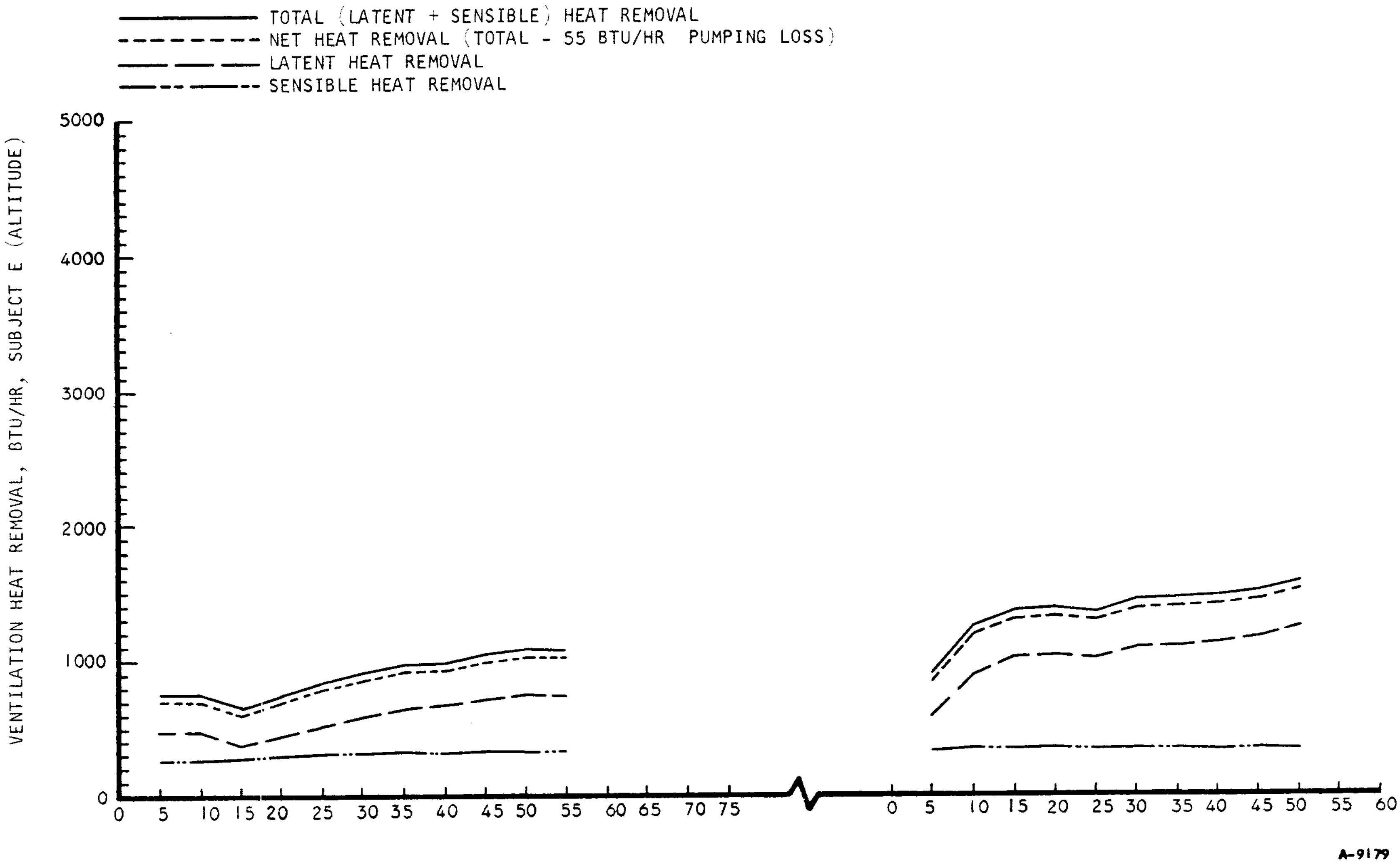


Figure 48. Ventilation Heat Removal, Subject E (Altitude)

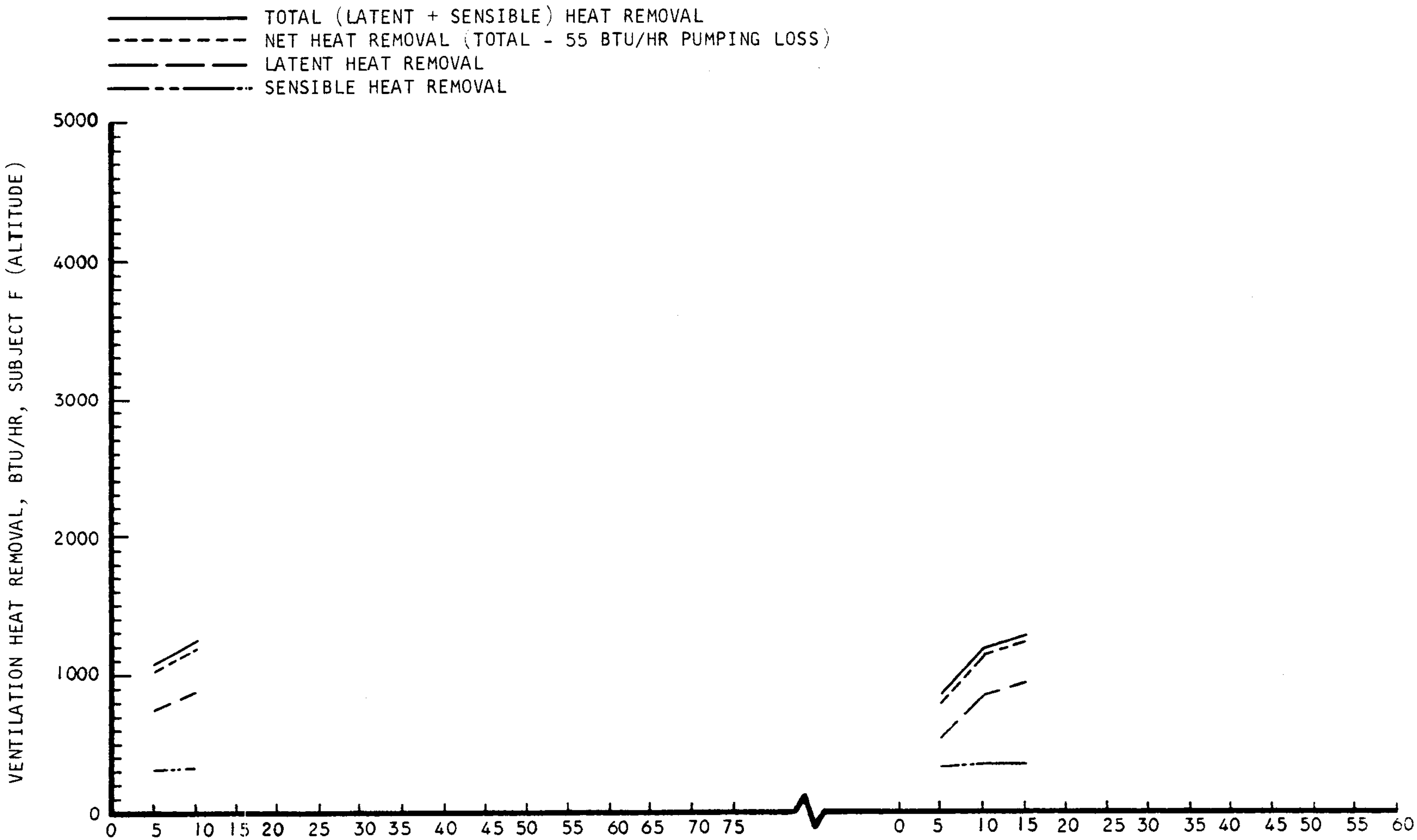


Figure 49. Ventilation Heat Removal, Subject F (Altitude)

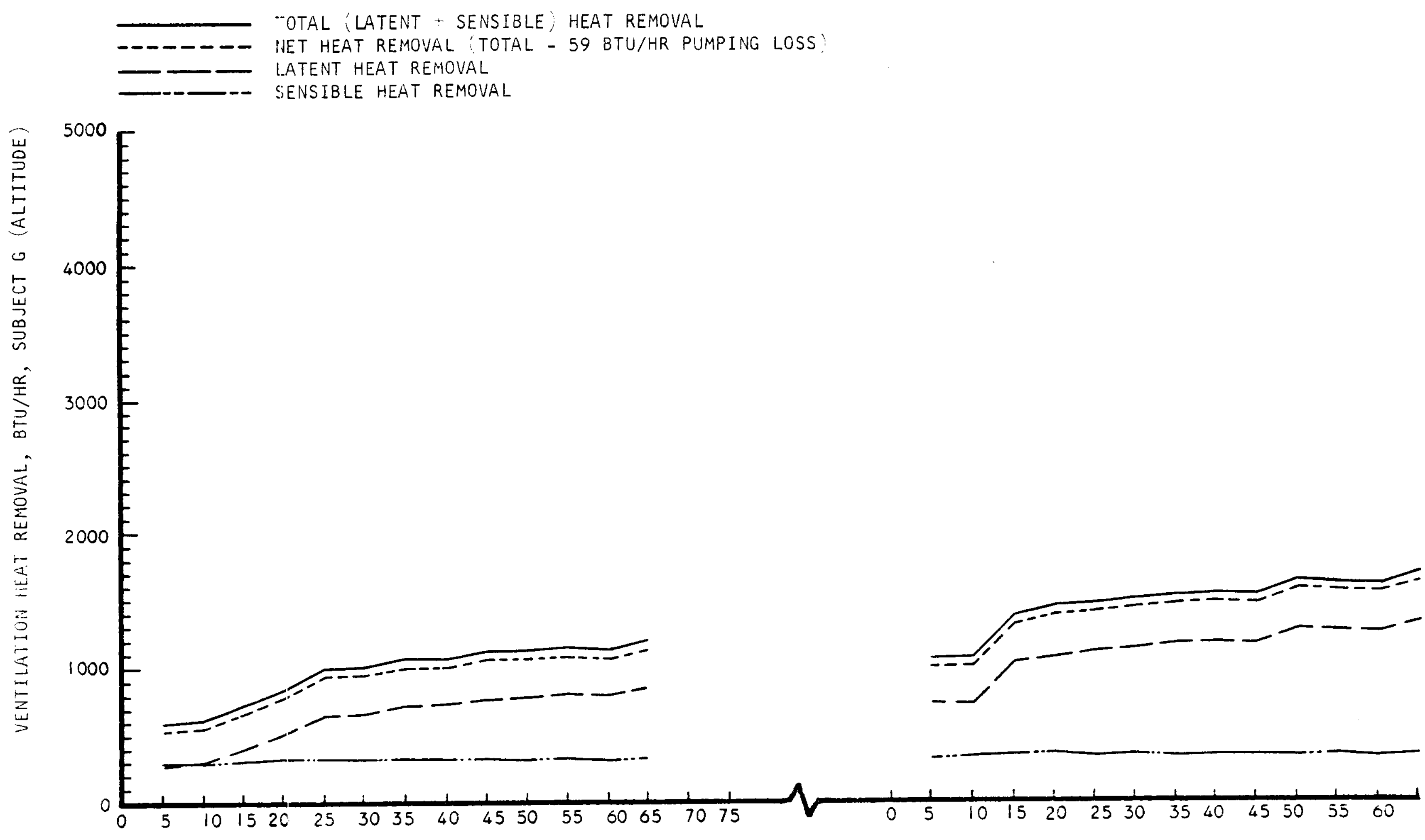


Figure 50. Ventilation Heat Removal, Subject G (Altitude)

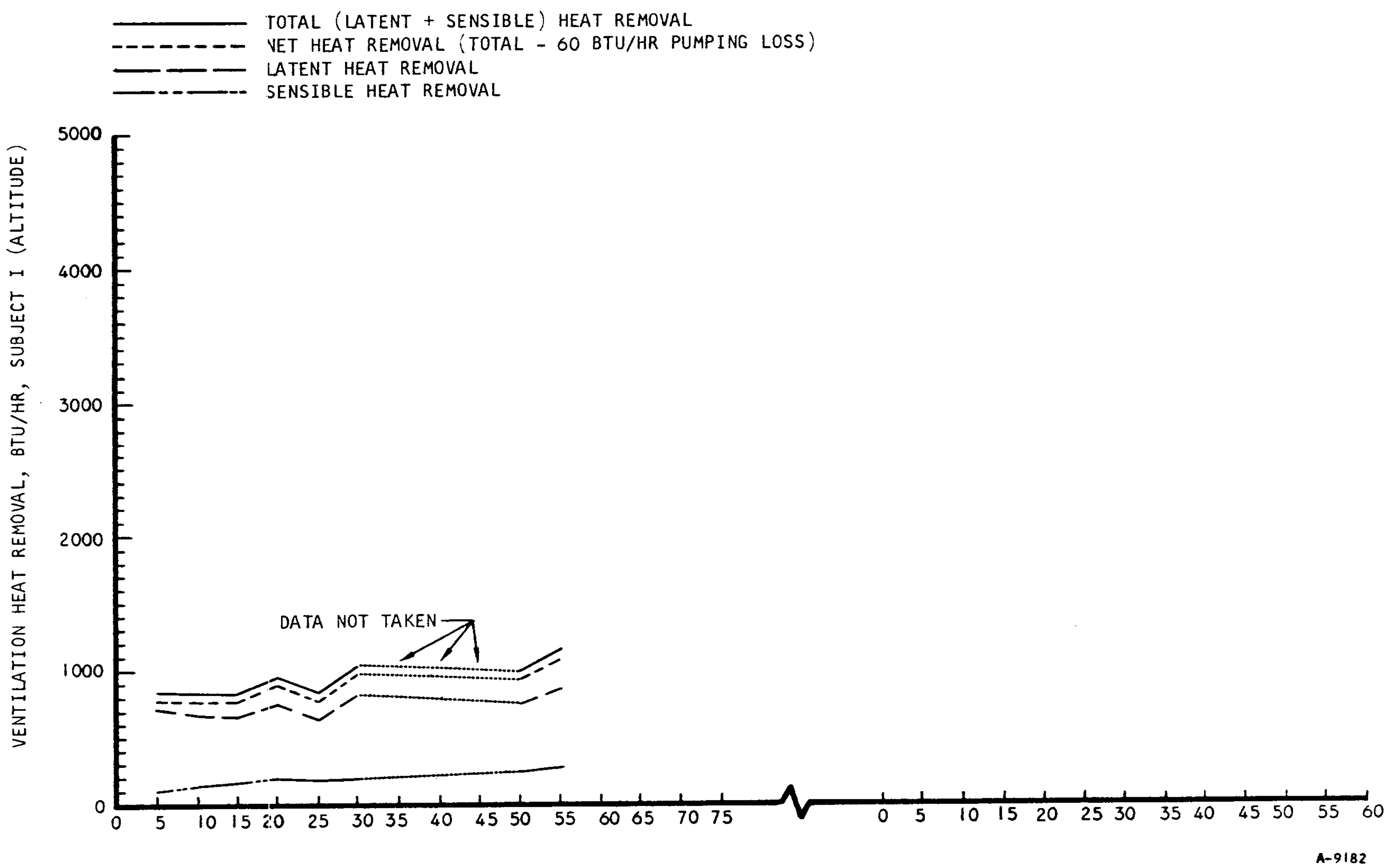


Figure 51. Ventilation Heat Removal, Subject I (Altitude)

SUIT OUTLET DRY-BULB TEMPERATURE

This section contains the graphs of the dry-bulb temperatures measured inside the suit ventilation exhaust fitting (Figures 52 through 61).

The curves at left and at right in each figure represent values taken at the low and high work rates, respectively.

These figures show that the outlet dry-bulb temperatures rise to a higher value and become asymptotic more rapidly at sea level than at altitude.

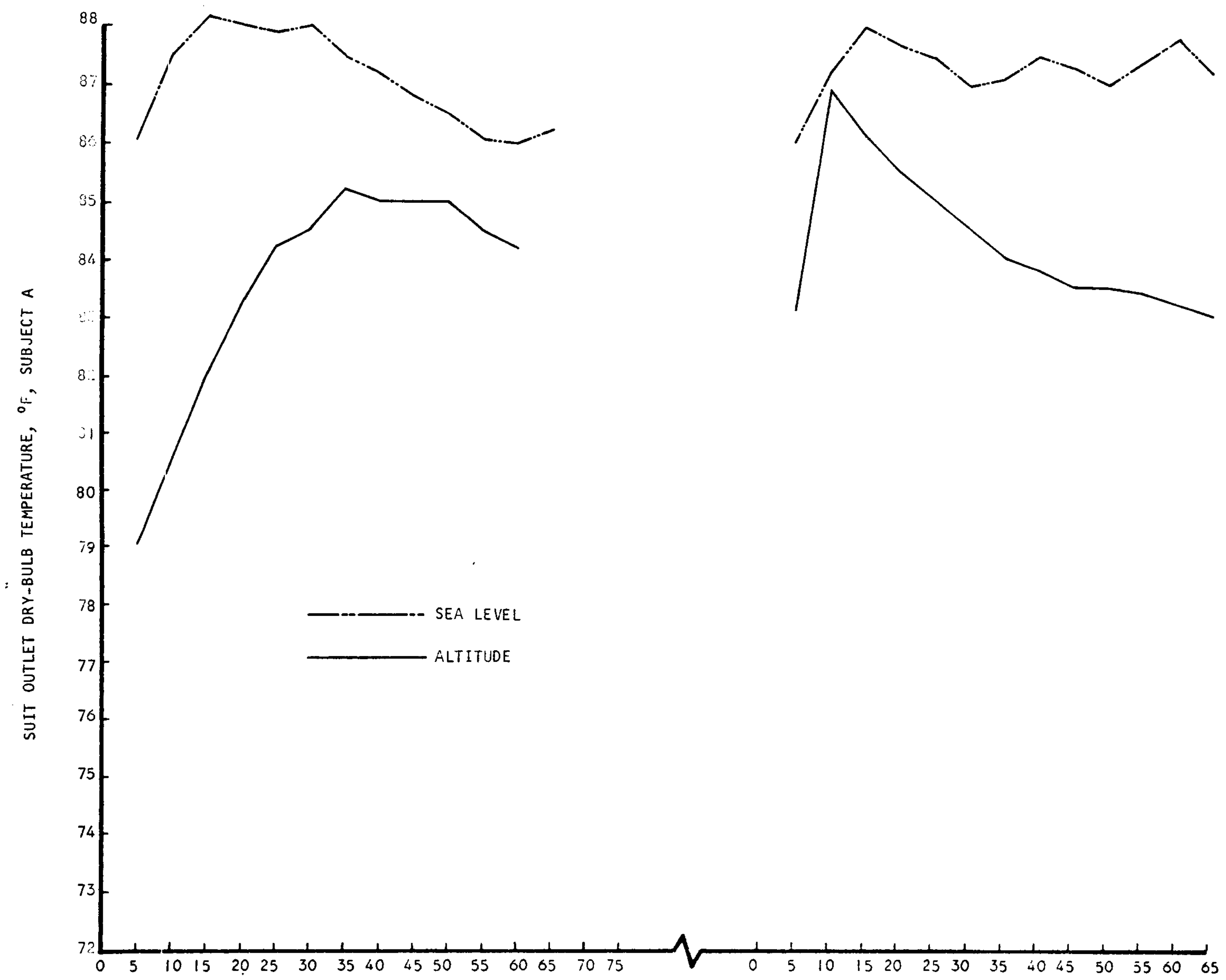


Figure 52. Suit Outlet Dry-Bulb Temperature, Subject A

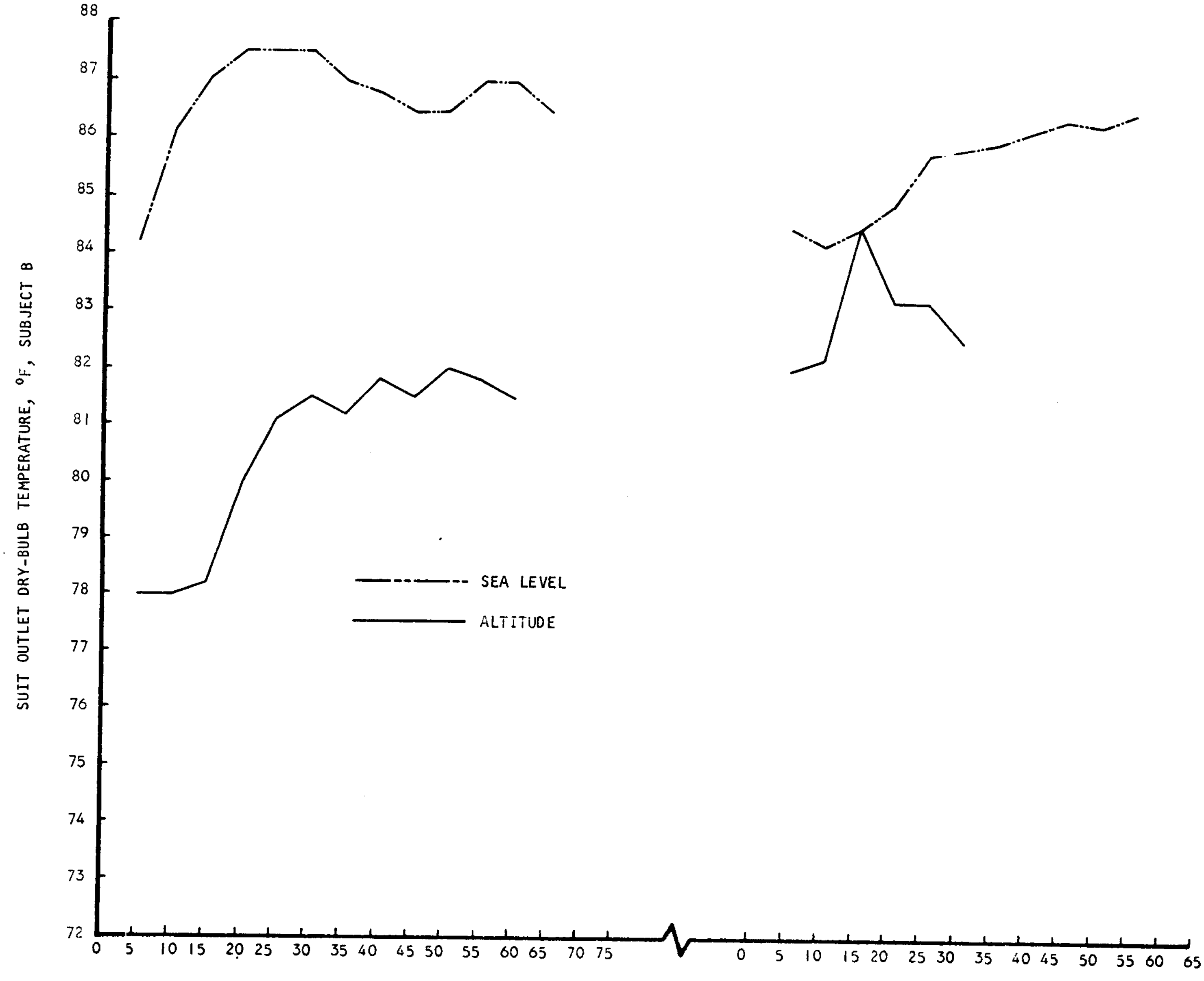


Figure 53. Suit Outlet Dry-Bulb Temperature, Subject B

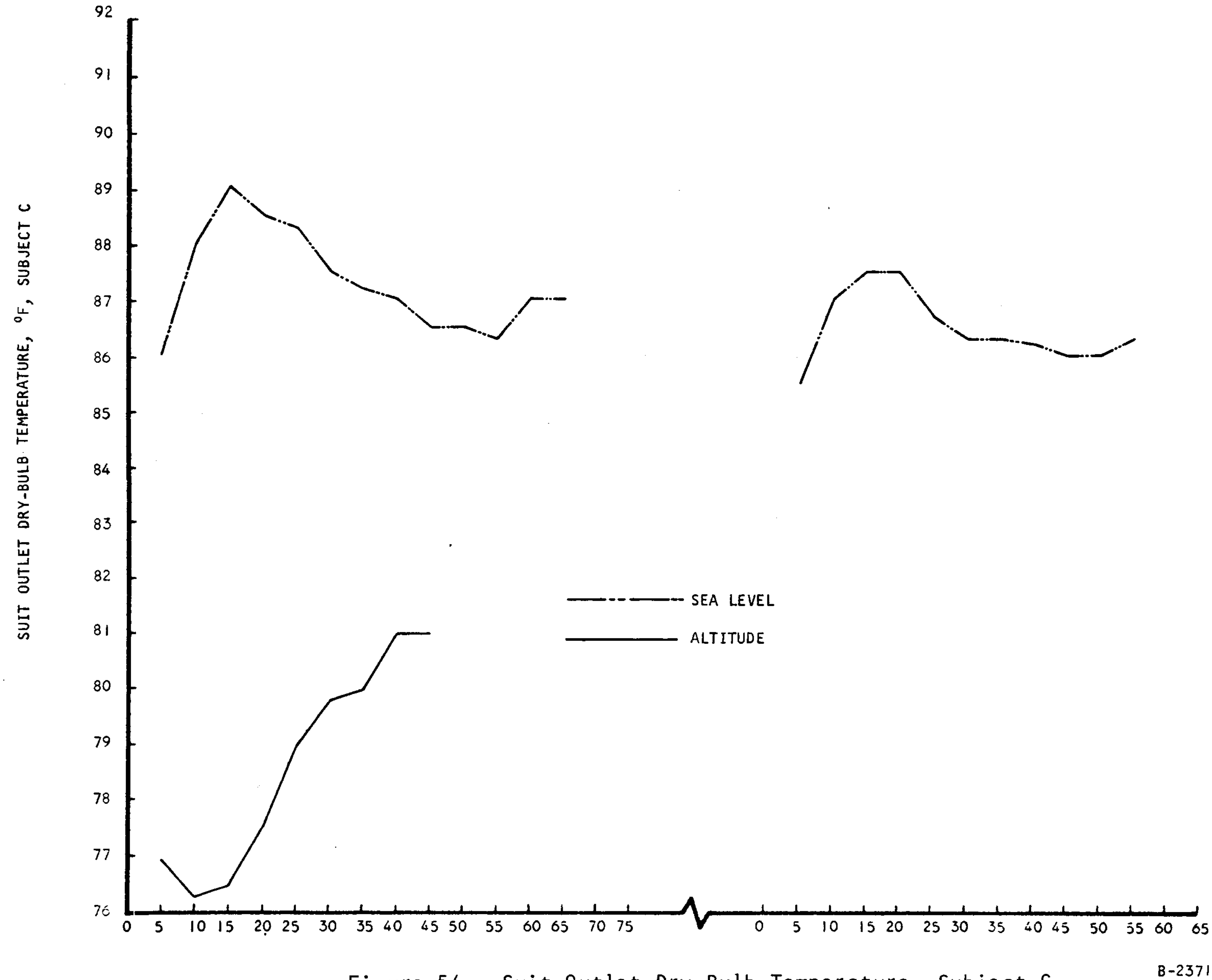


Figure 54. Suit Outlet Dry-Bulb Temperature, Subject C

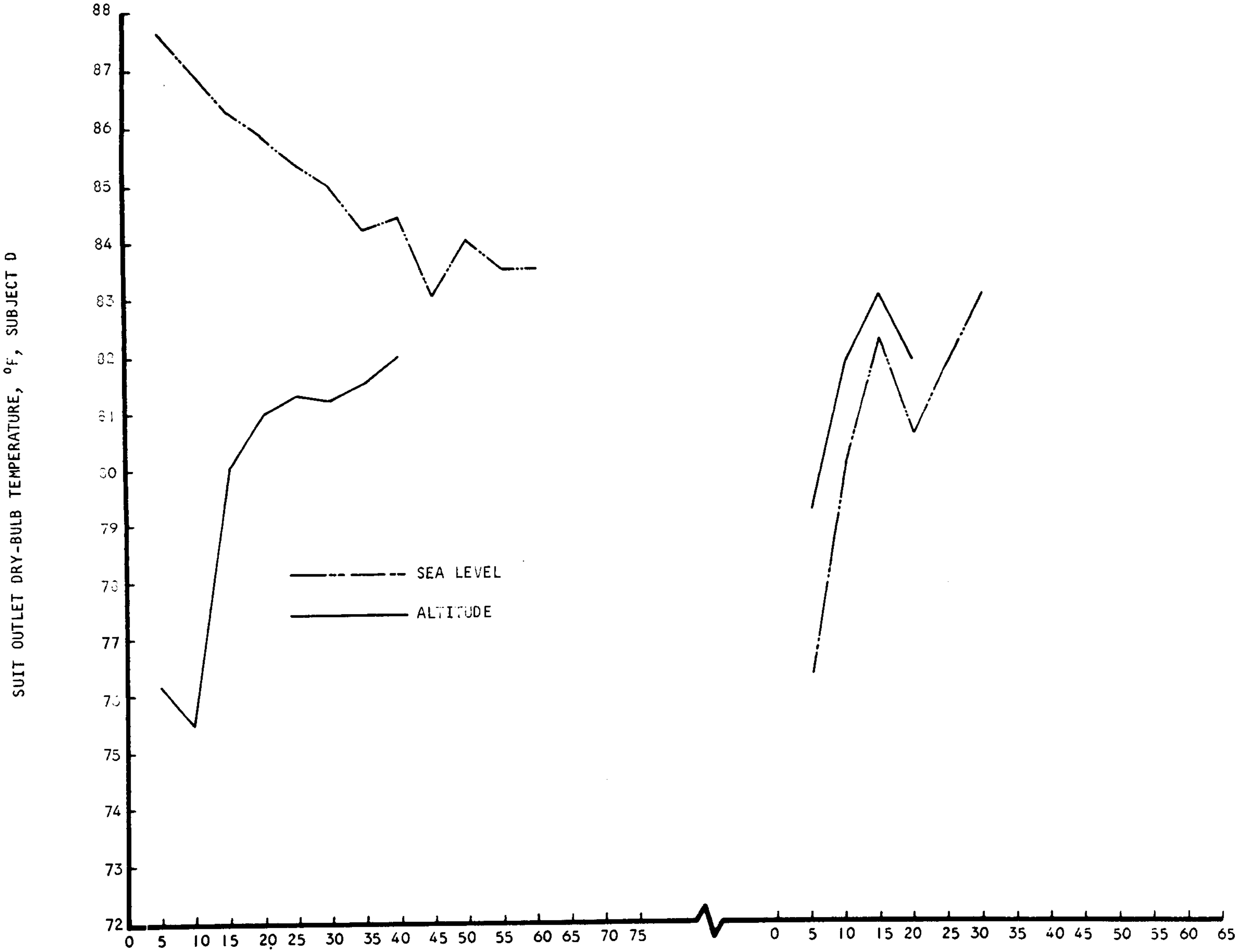


Figure 55. Suit Outlet Dry-Bulb Temperature, Subject D

B-2372

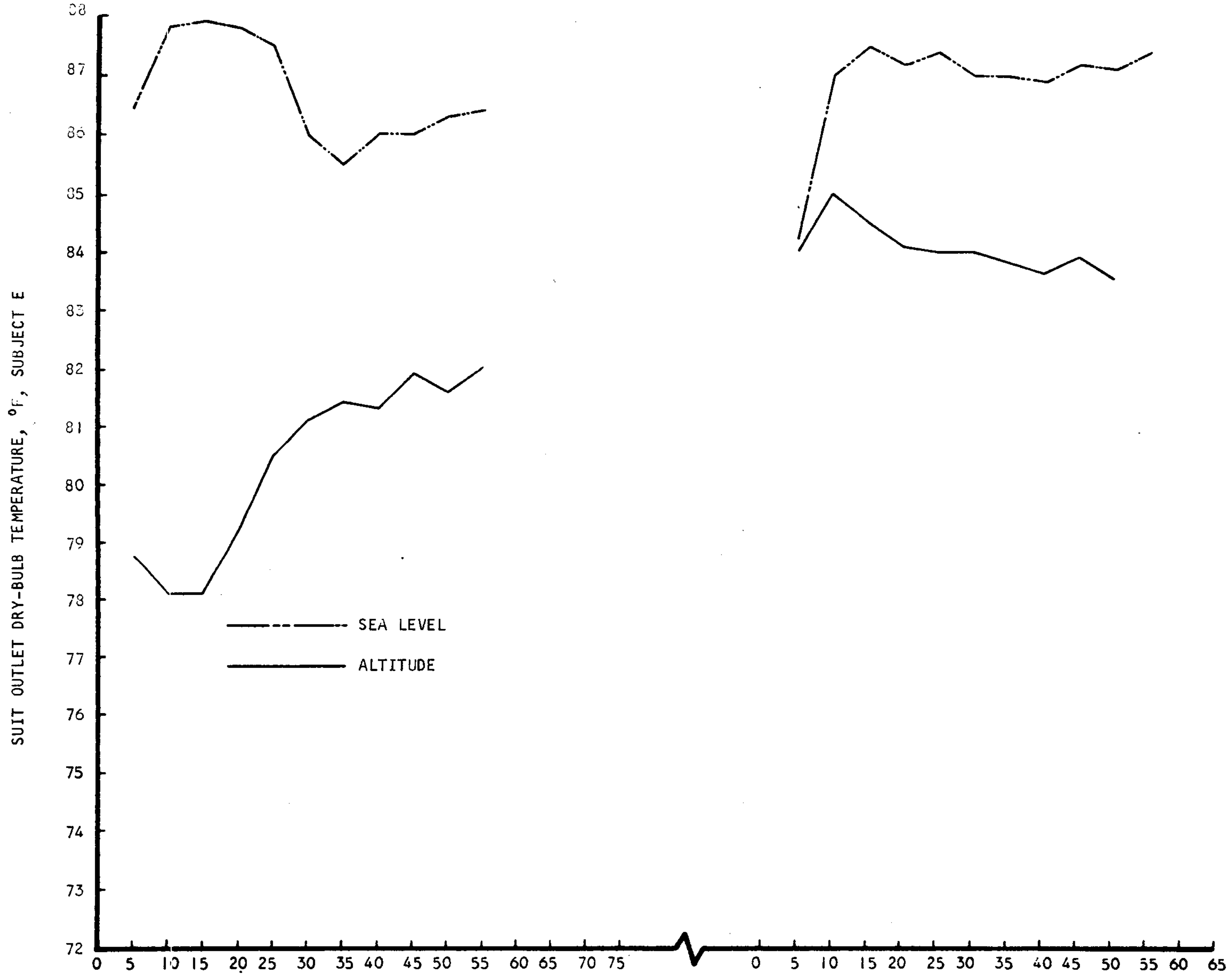


Figure 56. Suit Outlet Dry-Bulb Temperature, Subject E

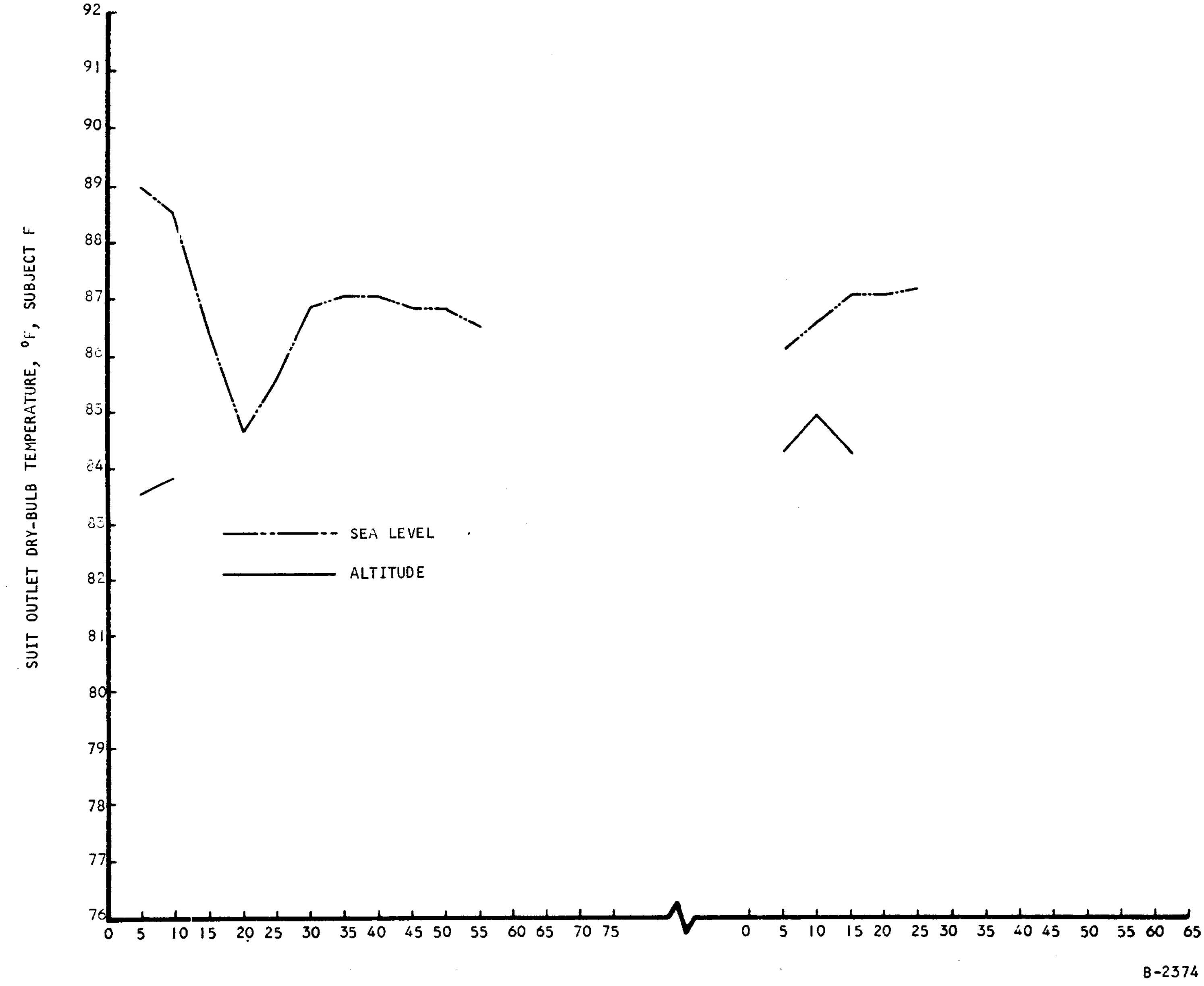


Figure 57. Suit Outlet Dry-Bulb Temperature, Subject F

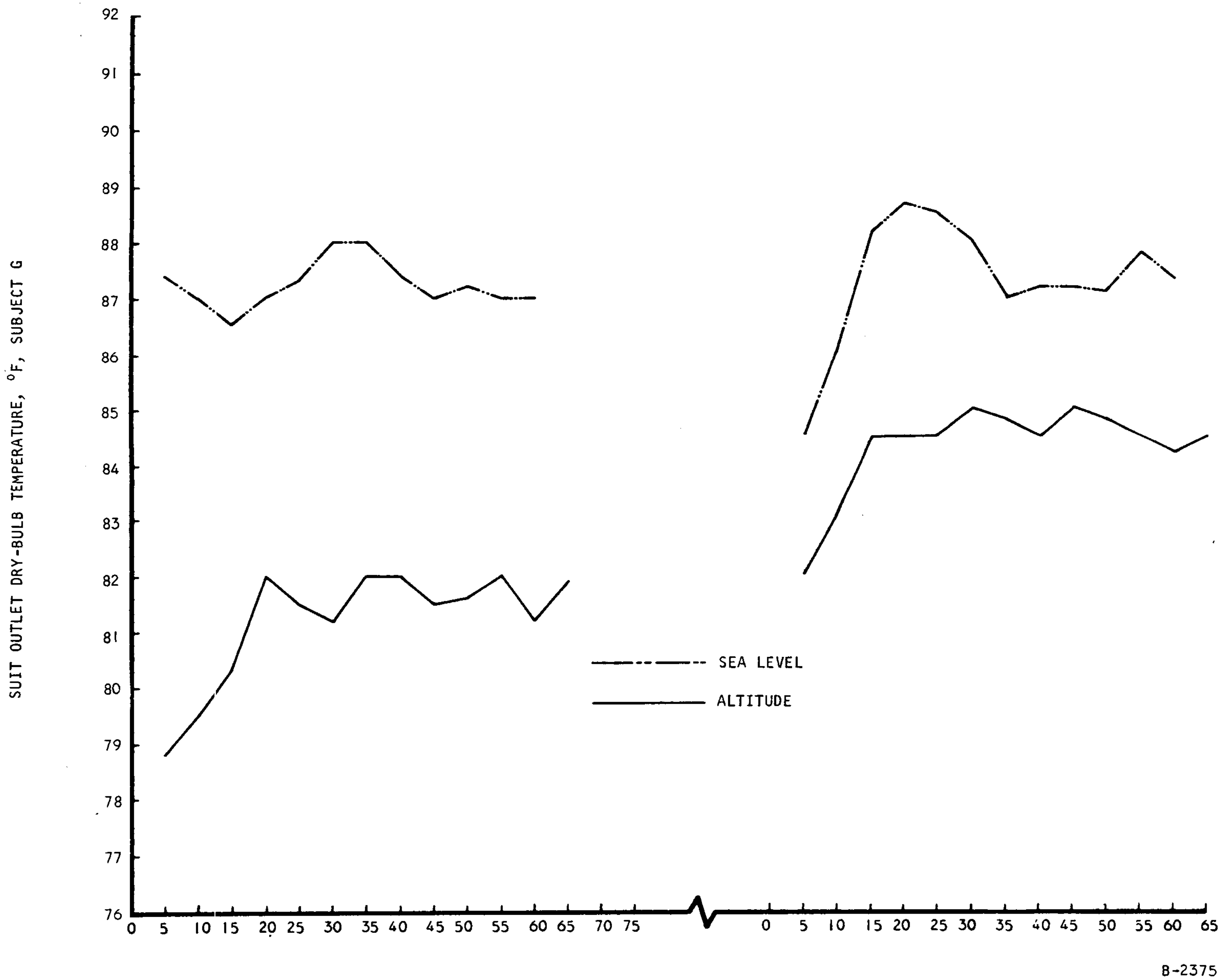


Figure 58. Suit Outlet Dry-Bulb Temperature, Subject G

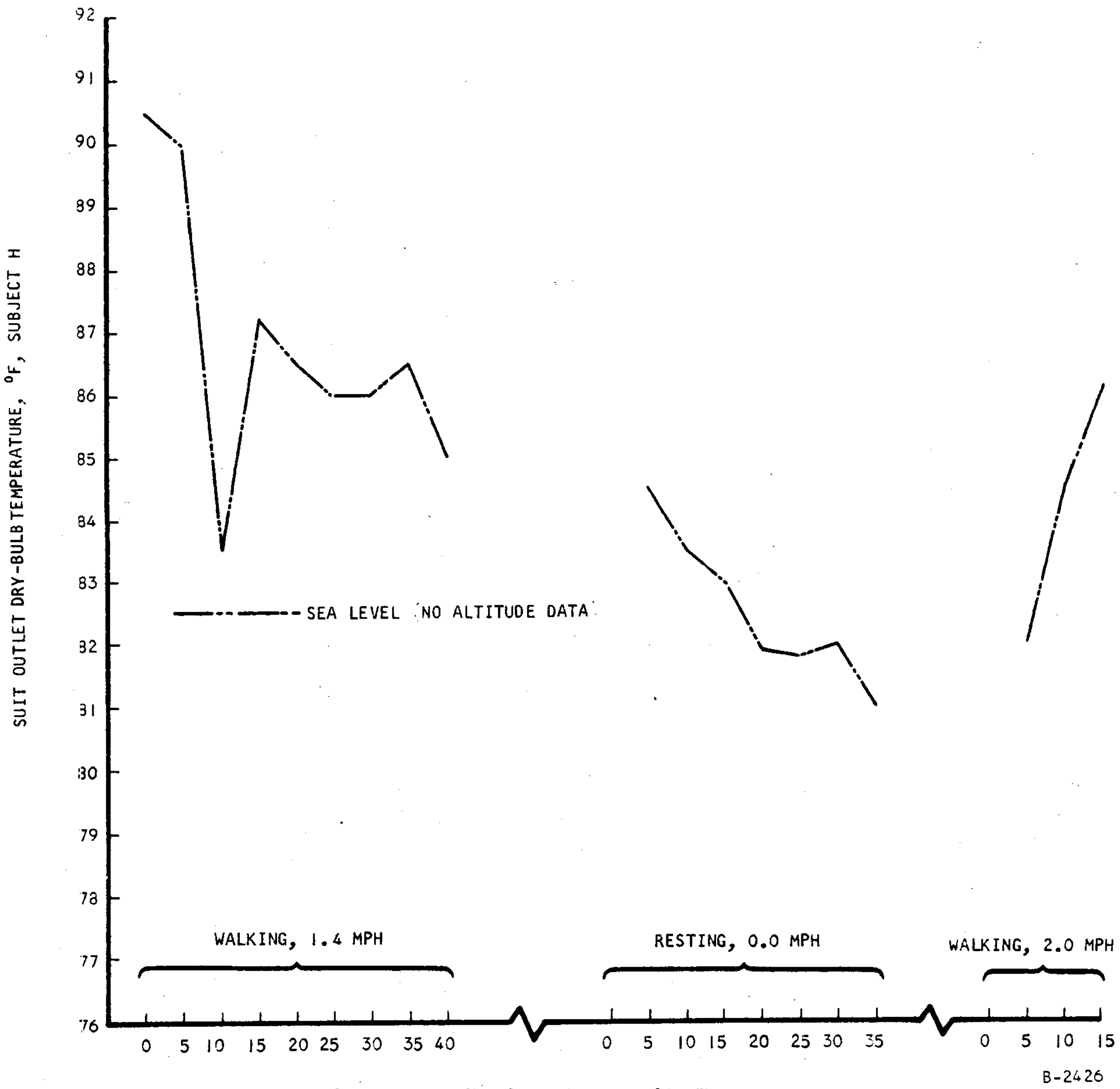


Figure 59. Suit Outlet Dry-Bulb Temperature, Subject H

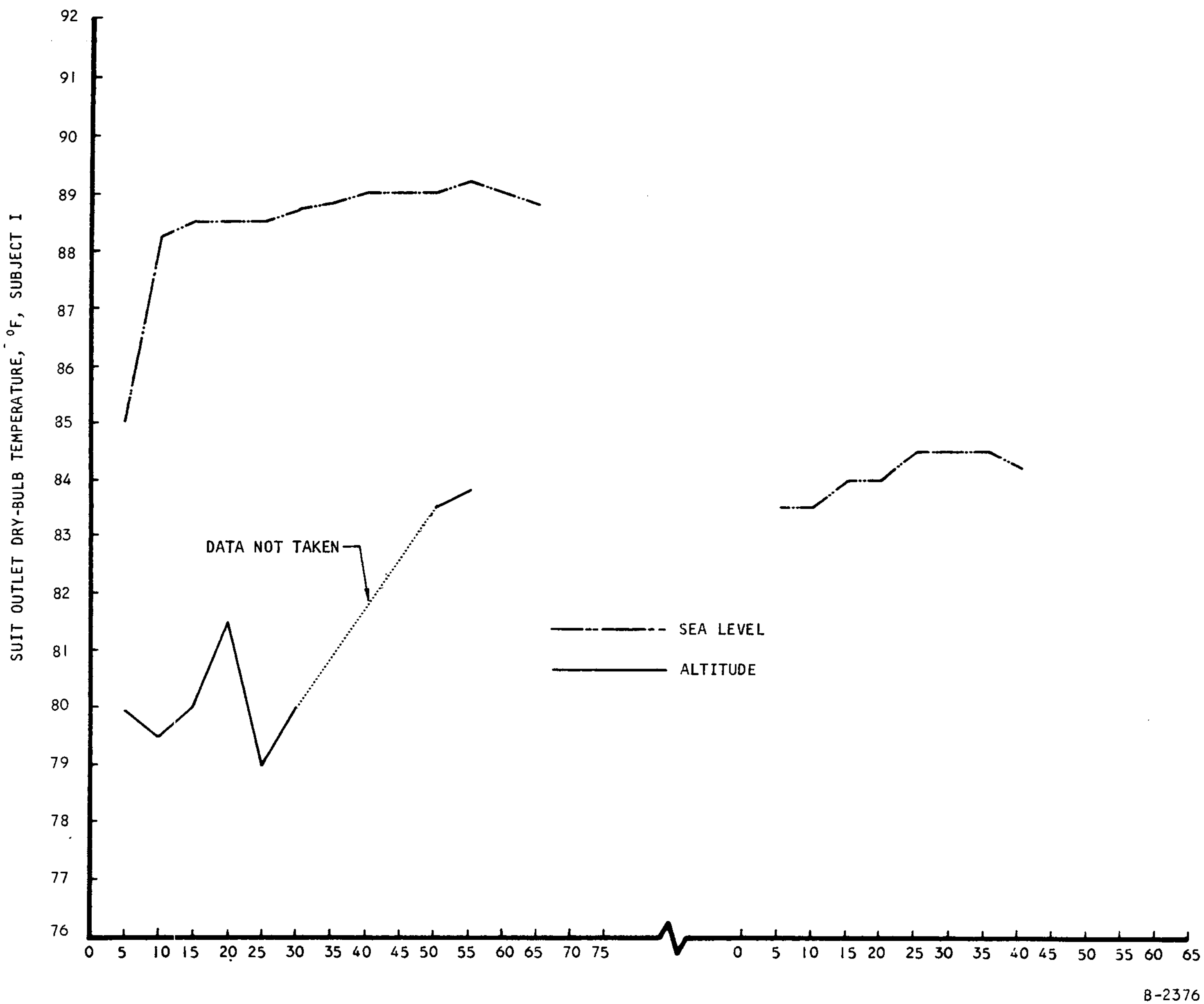
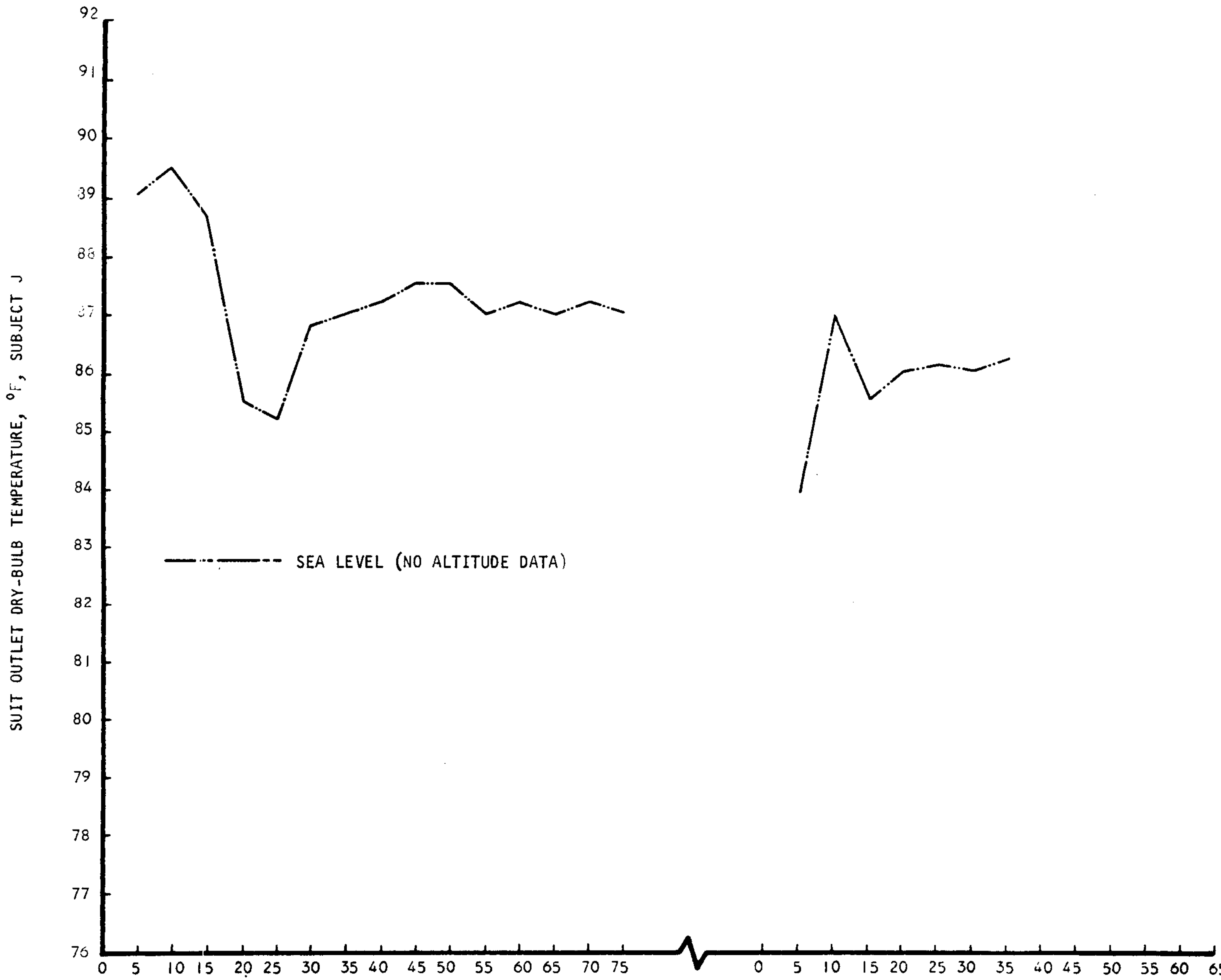


Figure 60. Suit Outlet Dry-Bulb Temperature, Subject I



B-2377

Figure 61. Suit Outlet Dry-Bulb Temperature, Subject J

SUIT OUTLET DEW-POINT TEMPERATURE

Figures 62 through 71 contain data of the dew-point temperatures, in degrees Fahrenheit, of the suit ventilation exhaust gases. These dew points were determined for the gas at the suit outlet fitting.

The curves shown at left and at right in the figures represent data for low and high work levels, respectively.

These curves show that, as with dry-bulb temperature, dew-point temperature rises to a higher level and is asymptotic more rapidly at sea level than at altitude.

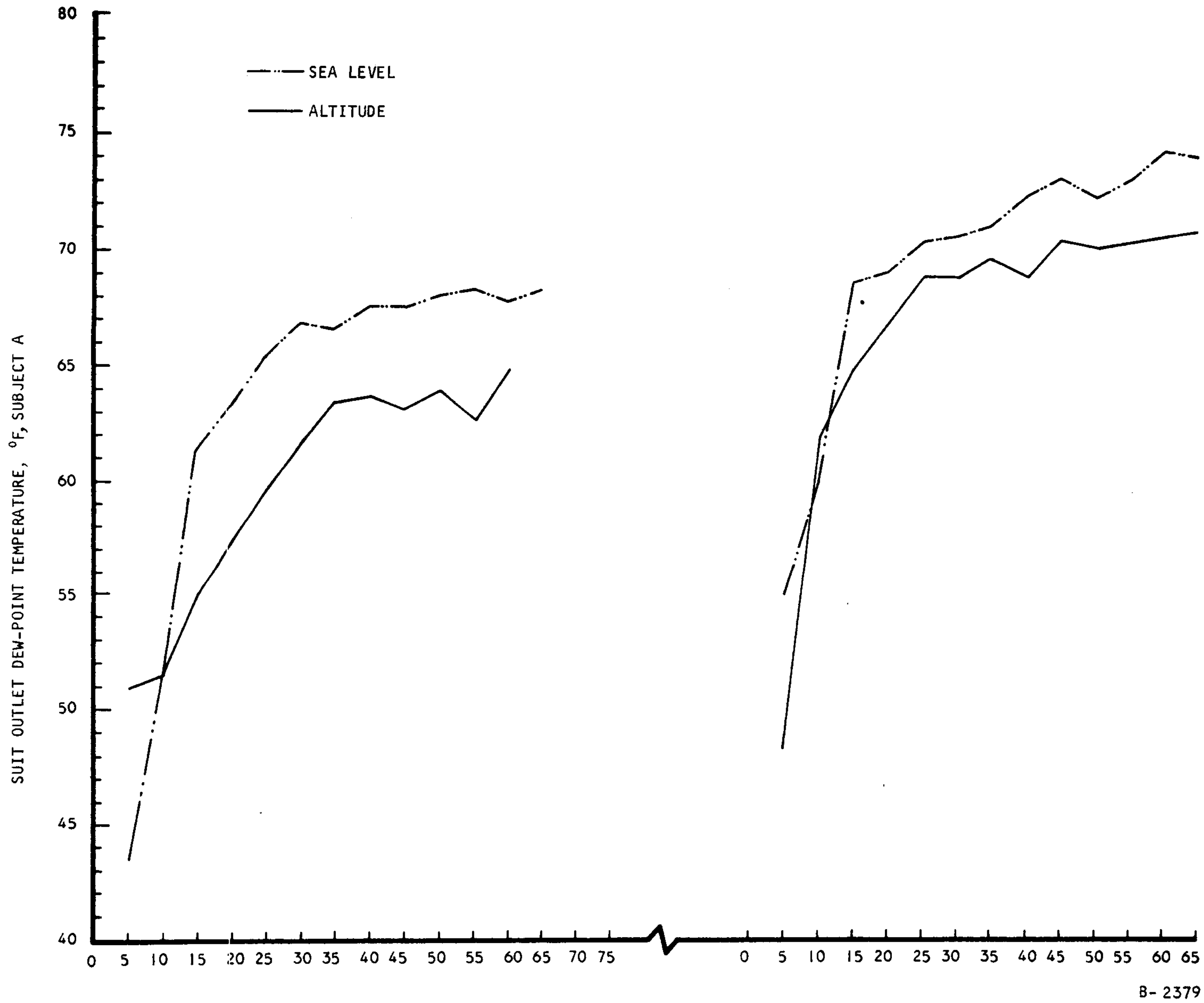


Figure 62. Suit Outlet Dew-Point Temperature, Subject A

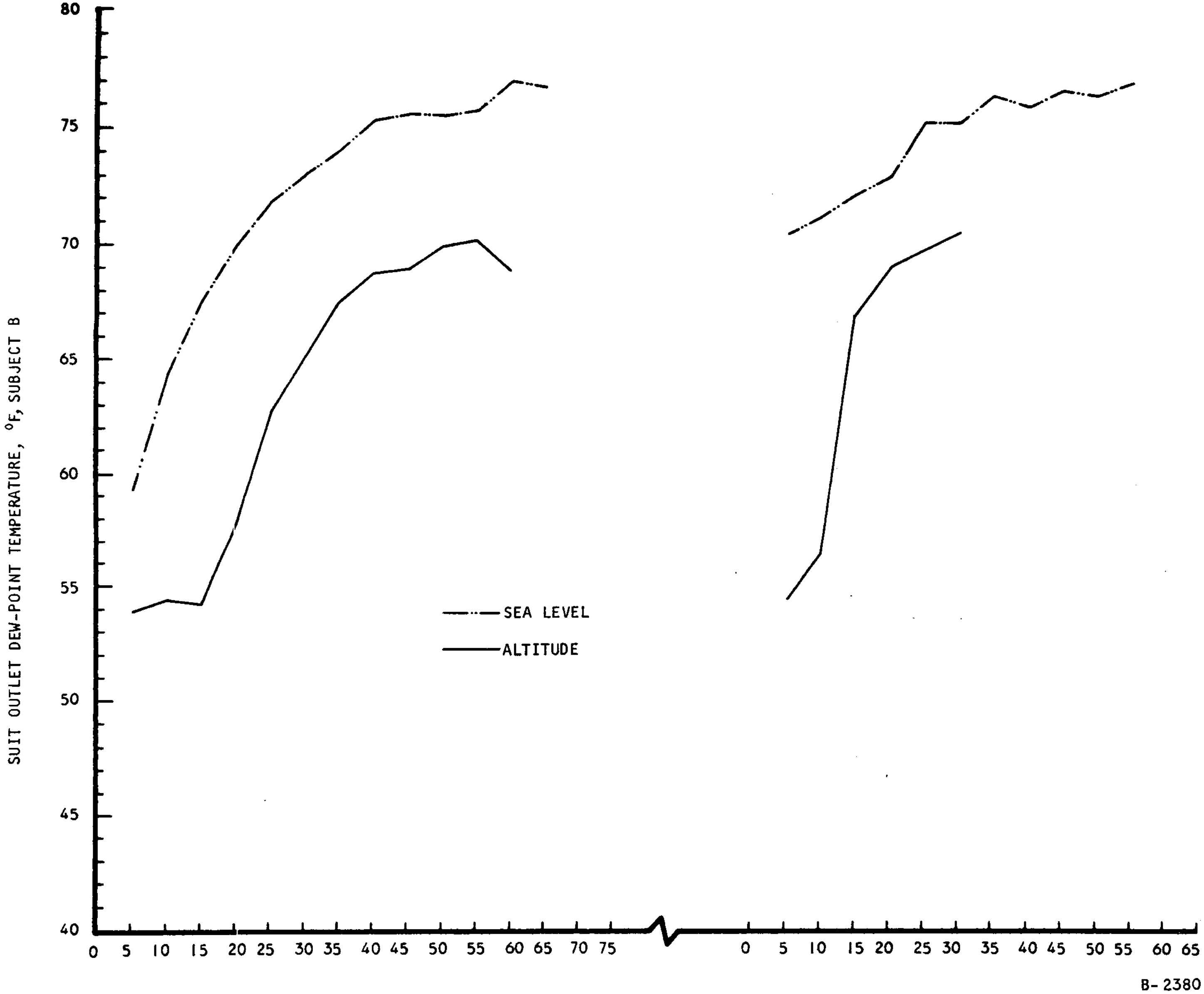


Figure 63. Suit Outlet Dew-Point Temperature, Subject B

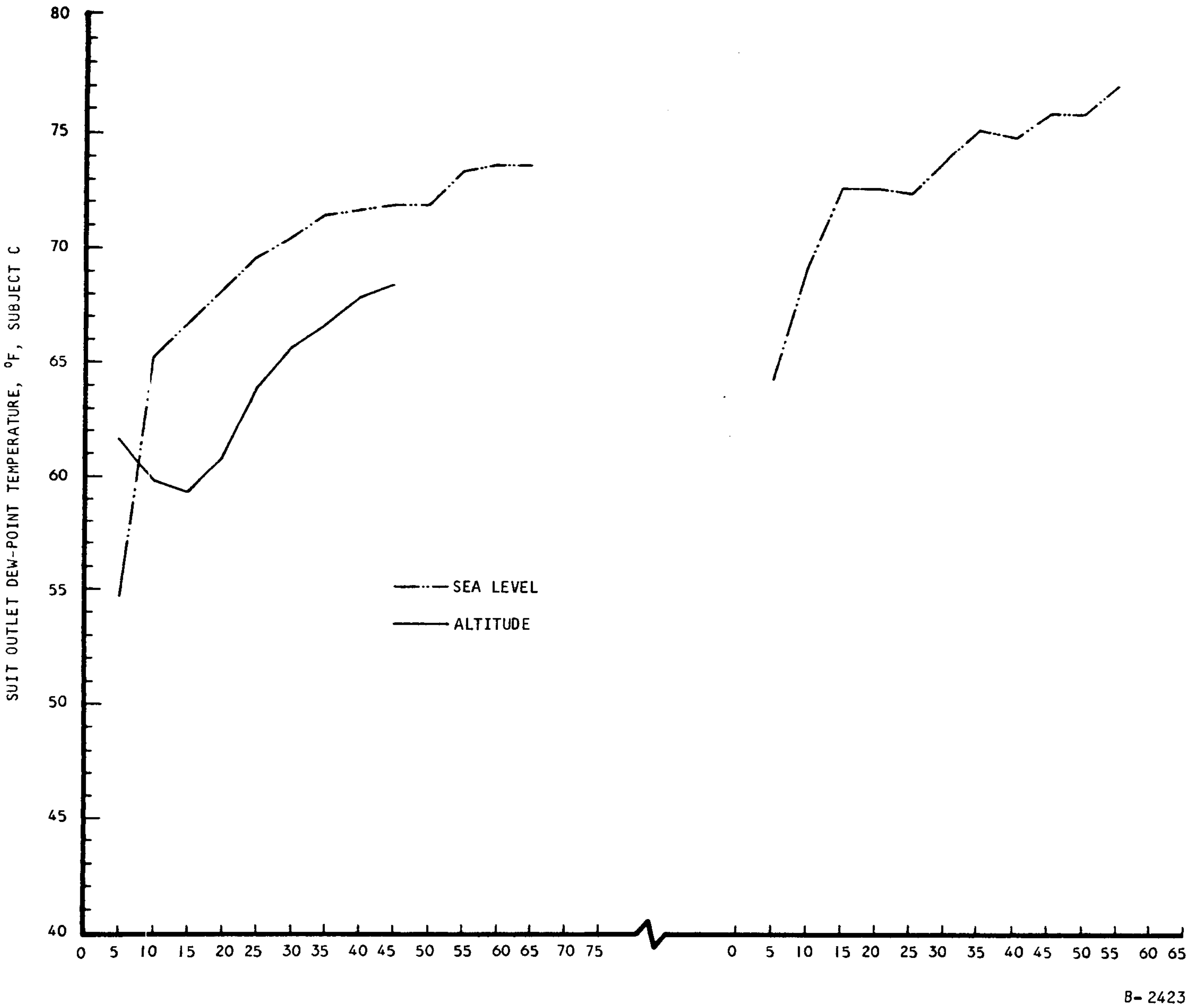


Figure 64. Suit Outlet Dew-Point Temperature, Subject C

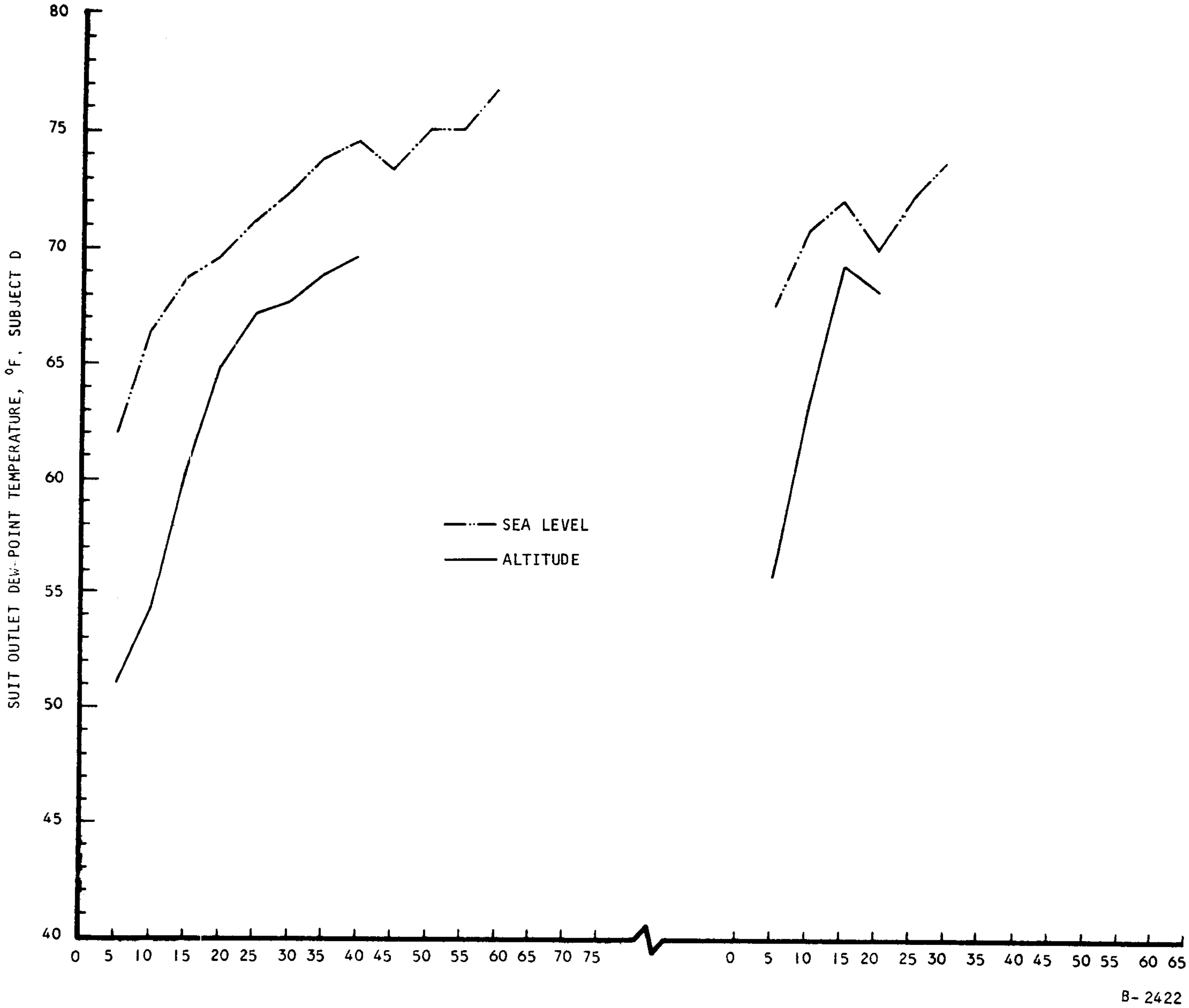


Figure 65. Suit Outlet Dew-Point Temperature, Subject D

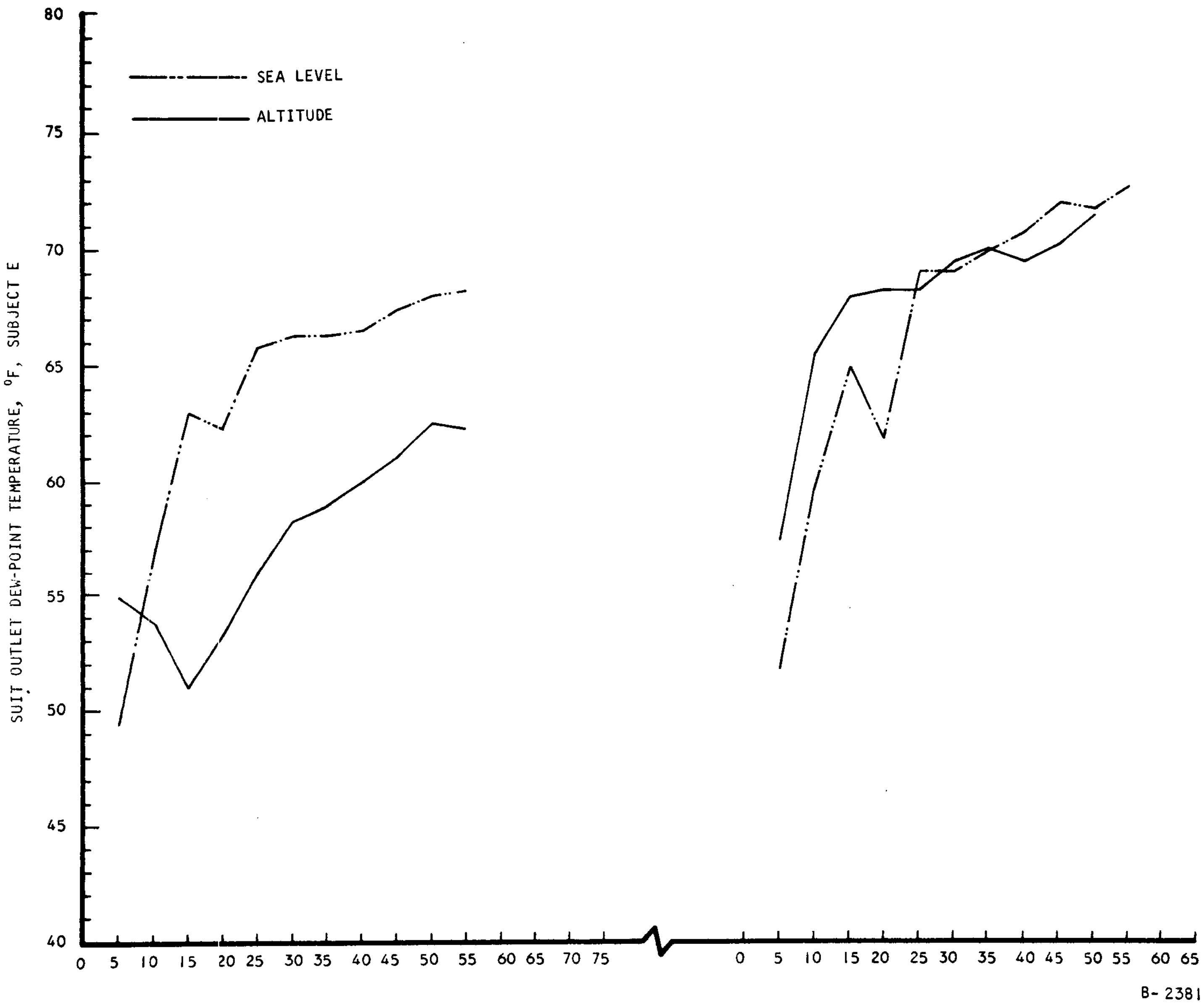


Figure 66. Suit Outlet Dew-Point Temperature, Subject E

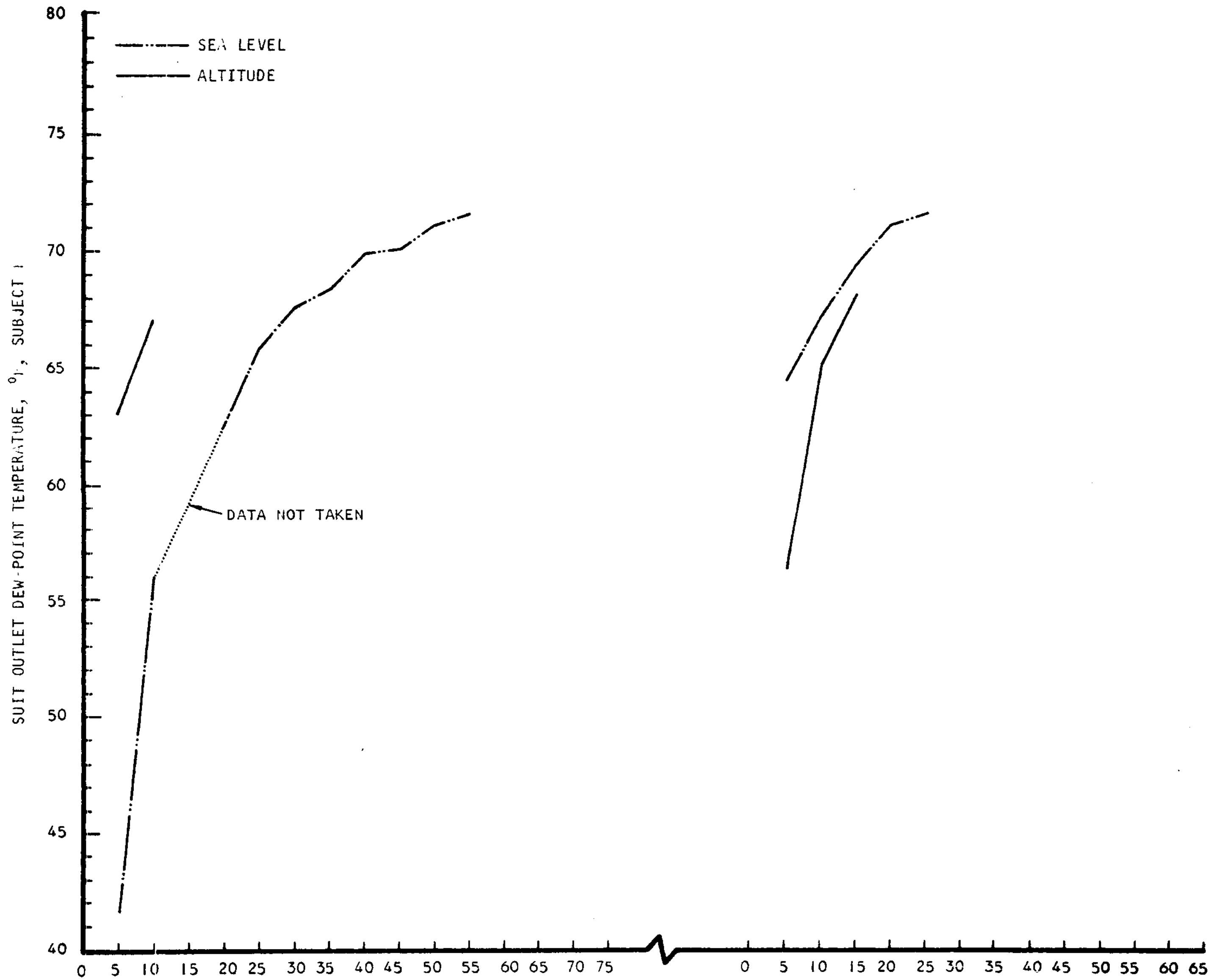


Figure 67. Suit Outlet Dew-Point Temperature, Subject F

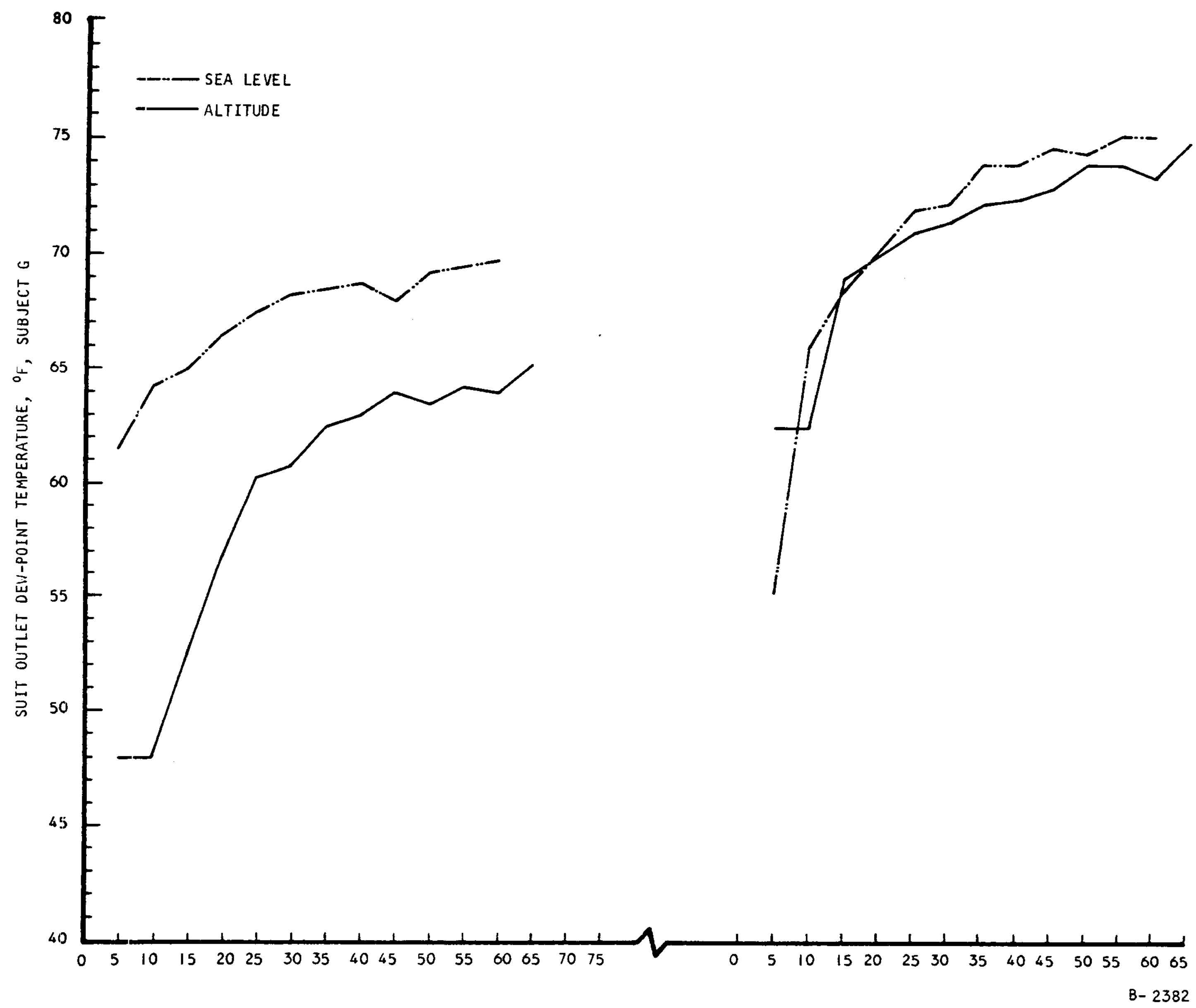


Figure 68. Suit Outlet Dew-Point Temperature, Subject G

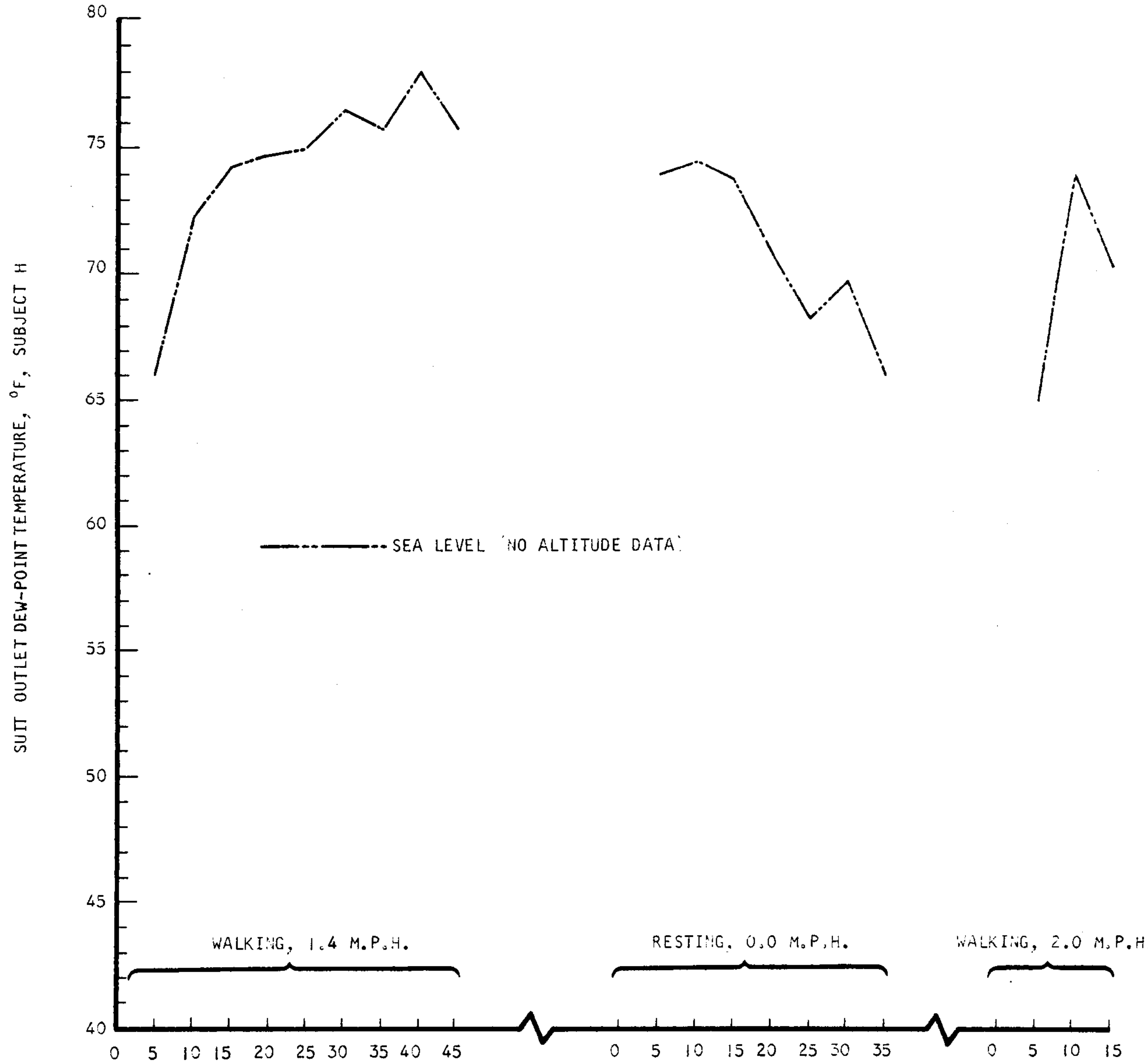


Figure 69. Suit Outlet Dew-Point Temperature, Subject H

B-2427

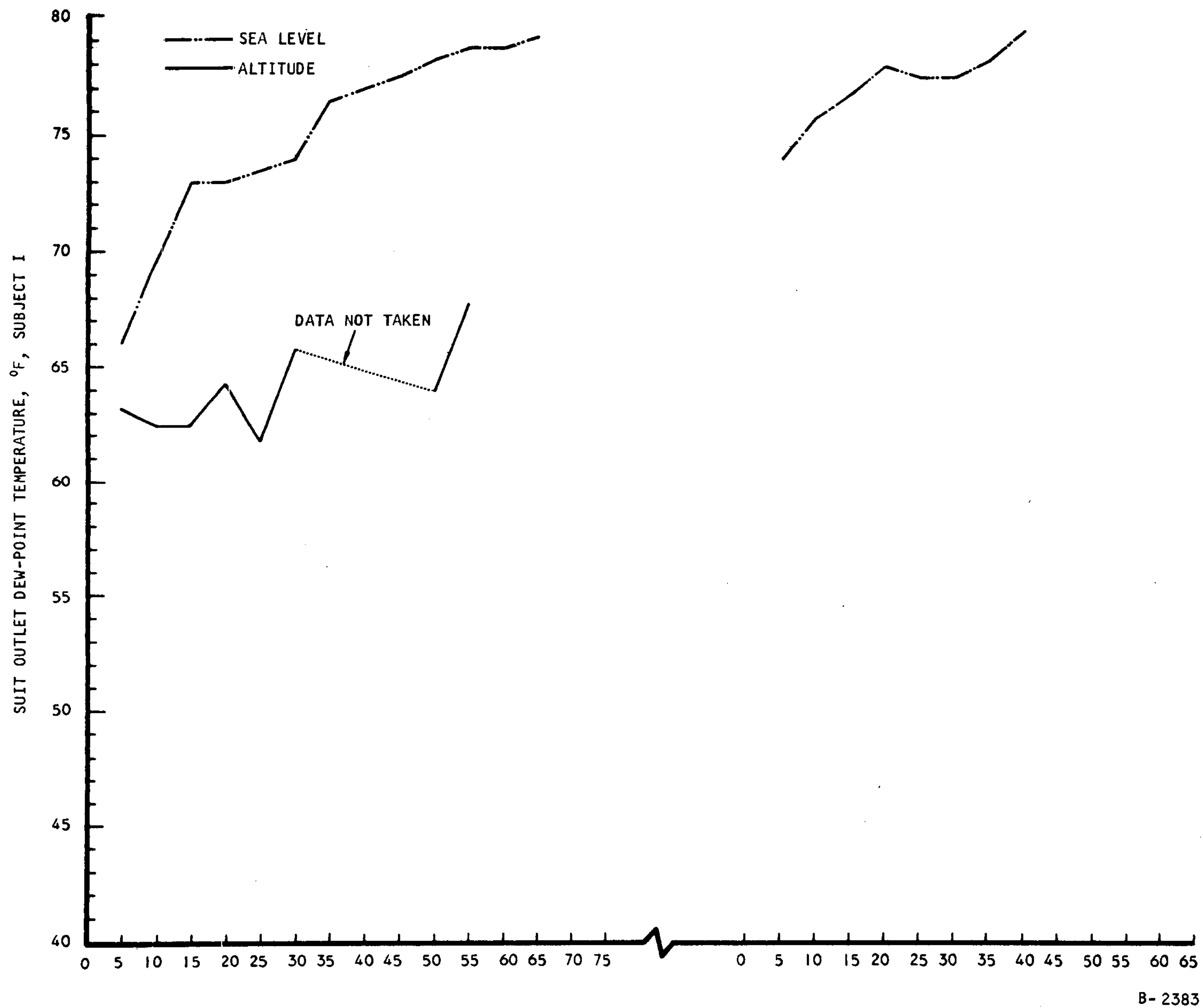


Figure 70. Suit Outlet Dew-Point Temperature, Subject I

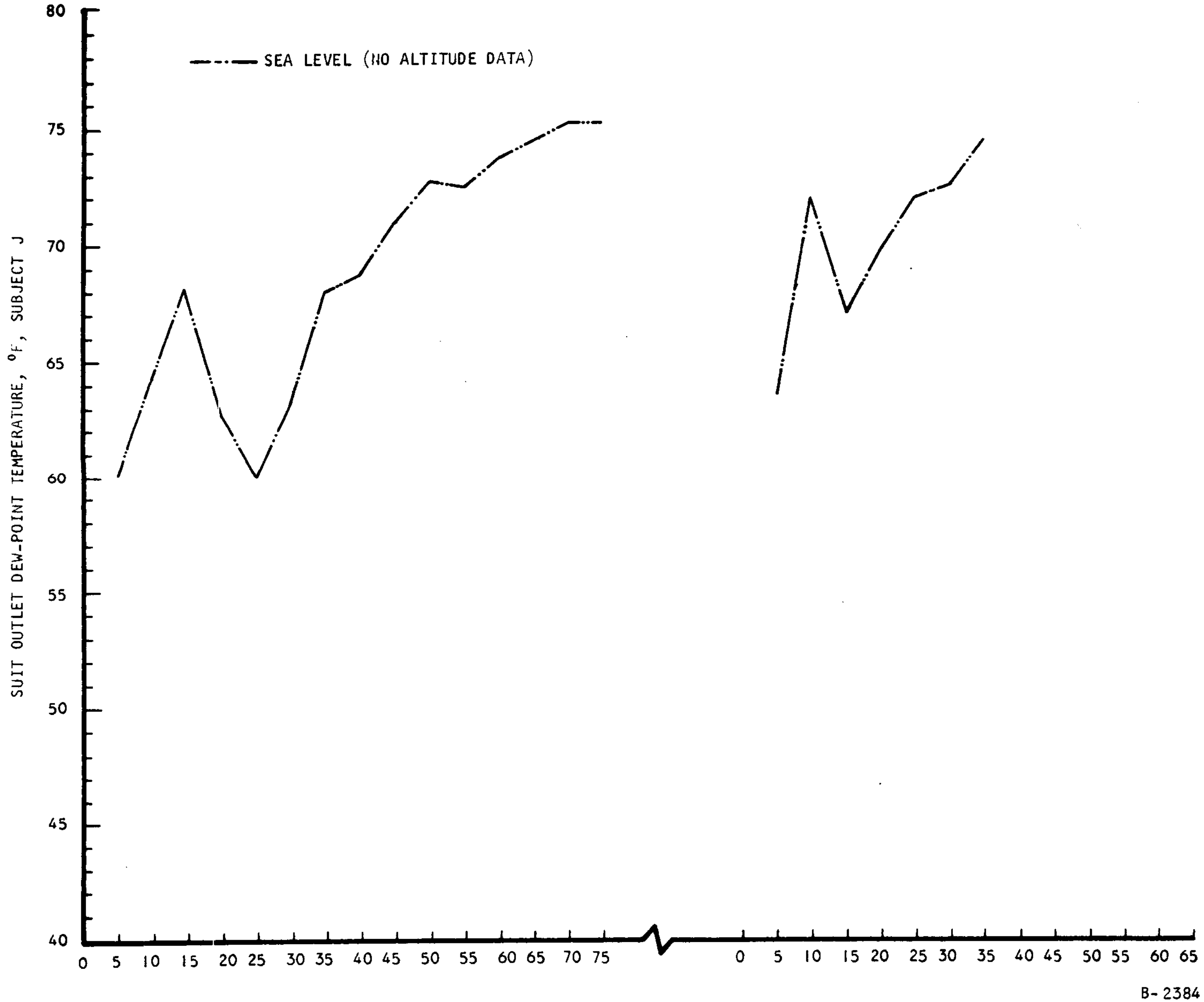


Figure 71. Suit Outlet Dew-Point Temperature, Subject J

RECTAL TEMPERATURE

As would be expected, rectal temperature rises steadily during exercise, generally with a slope proportional to the work rate (in Figures 72 through 81 the graphs on the left represent the 1.4 mph activity level, and those on the right represent the 2.0 mph level). Although the rectal temperature generally drops during the rest periods, it seldom fully recovers, and thus usually exhibits an overall rise for the test day. The relationship of rectal temperature to body heat storage is described in Section 7.

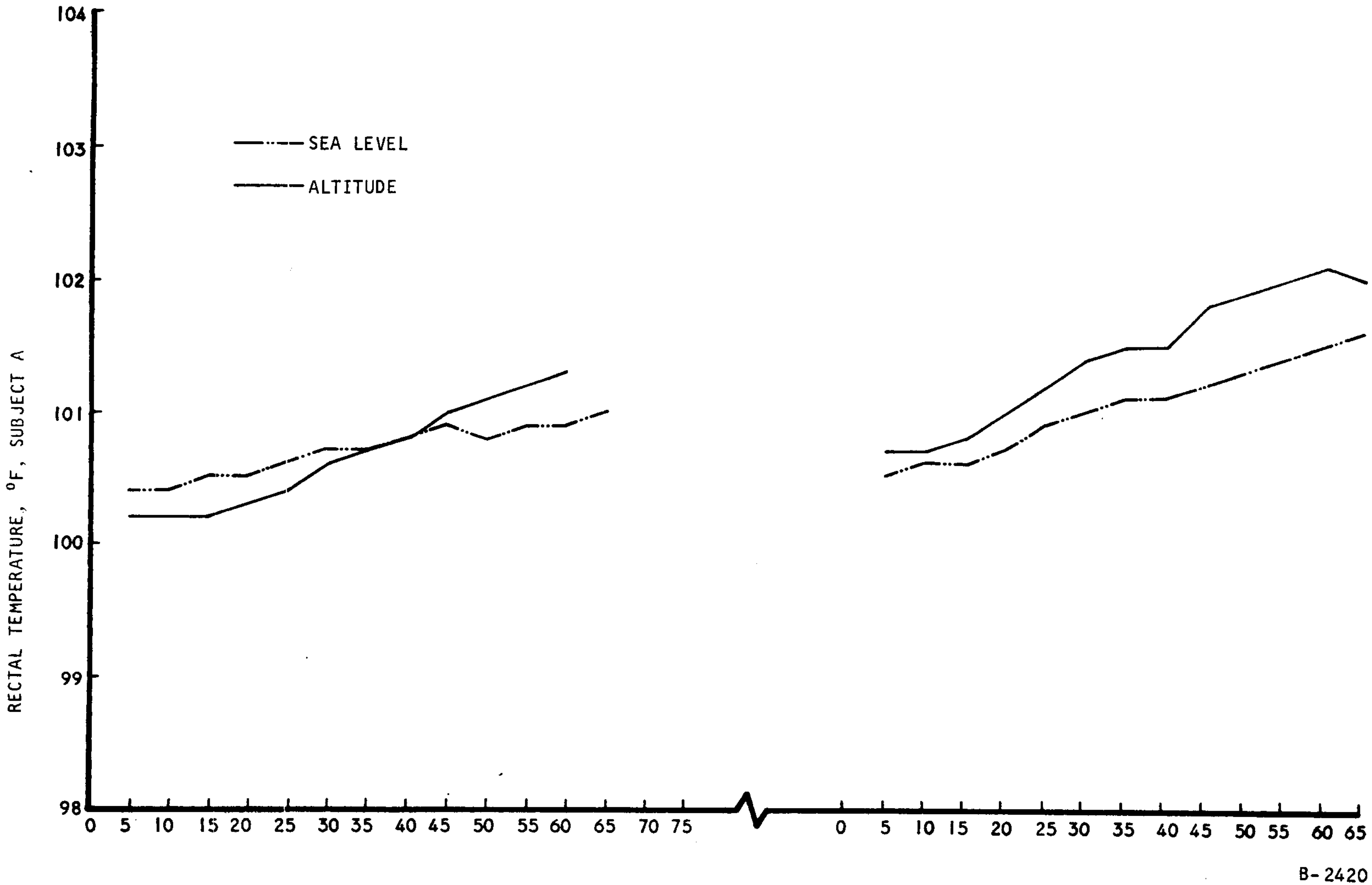


Figure 72. Rectal Temperature, Subject A

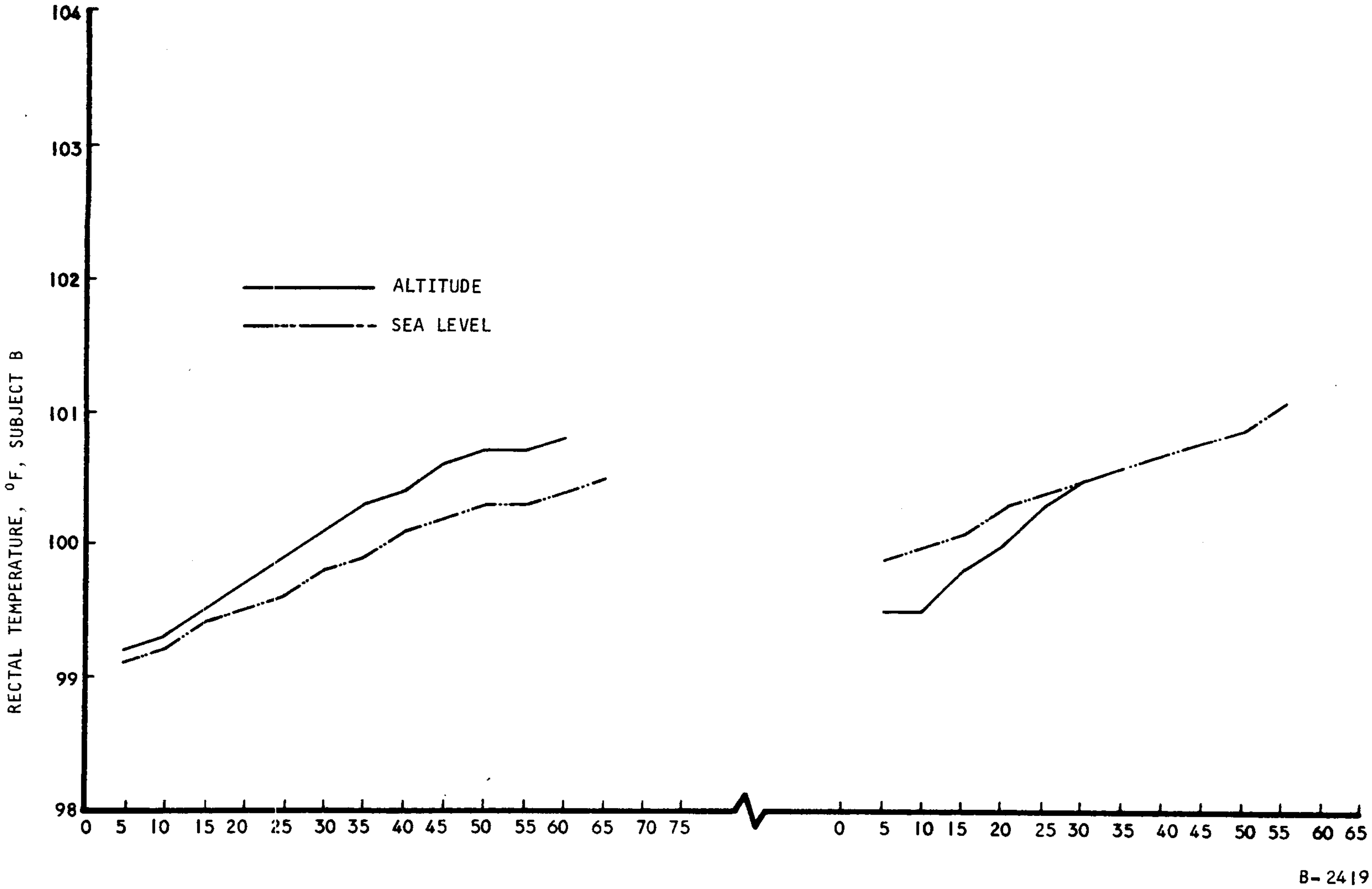


Figure 73. Rectal Temperature, Subject B

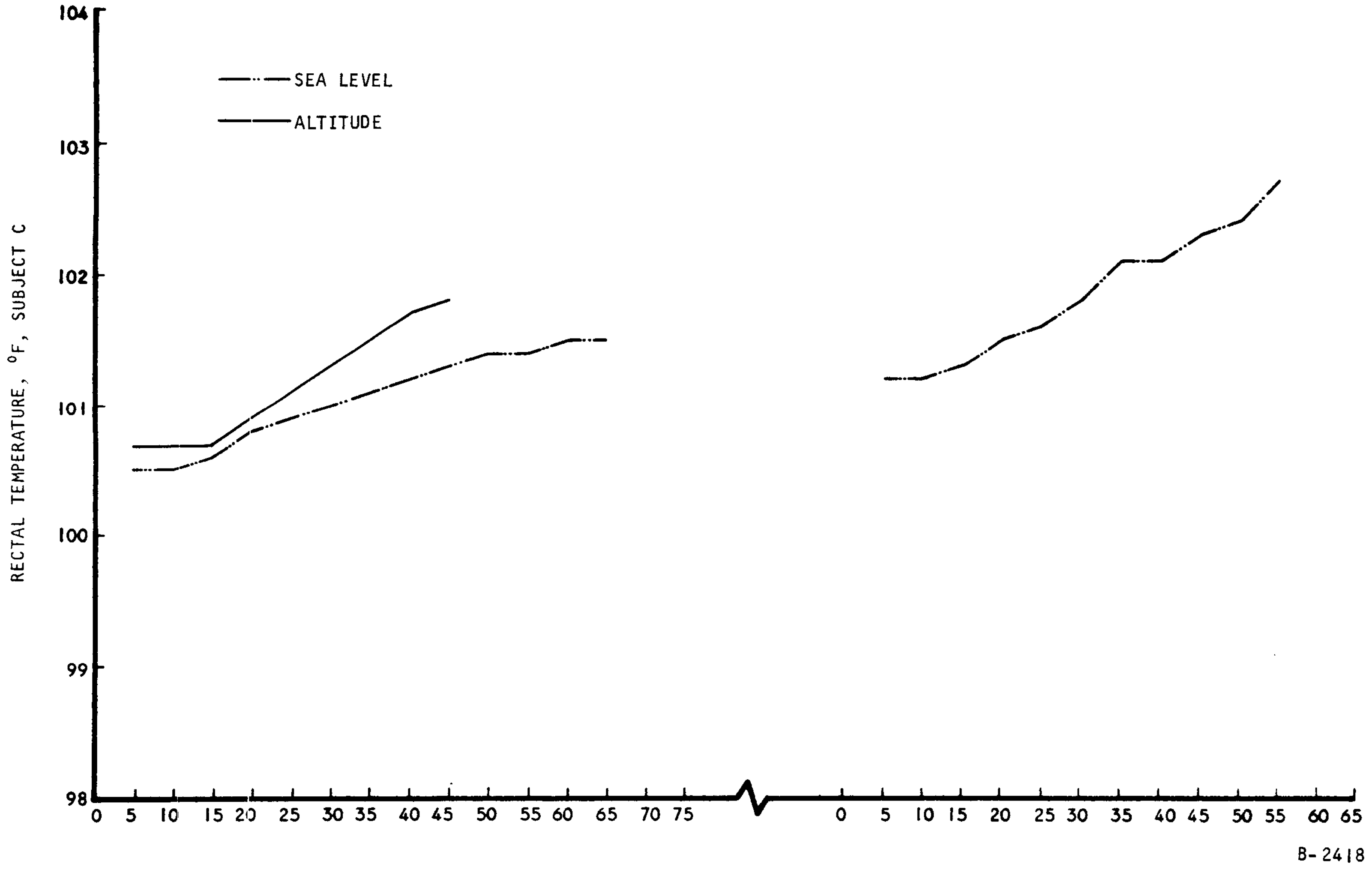


Figure 74. Rectal Temperature, Subject C

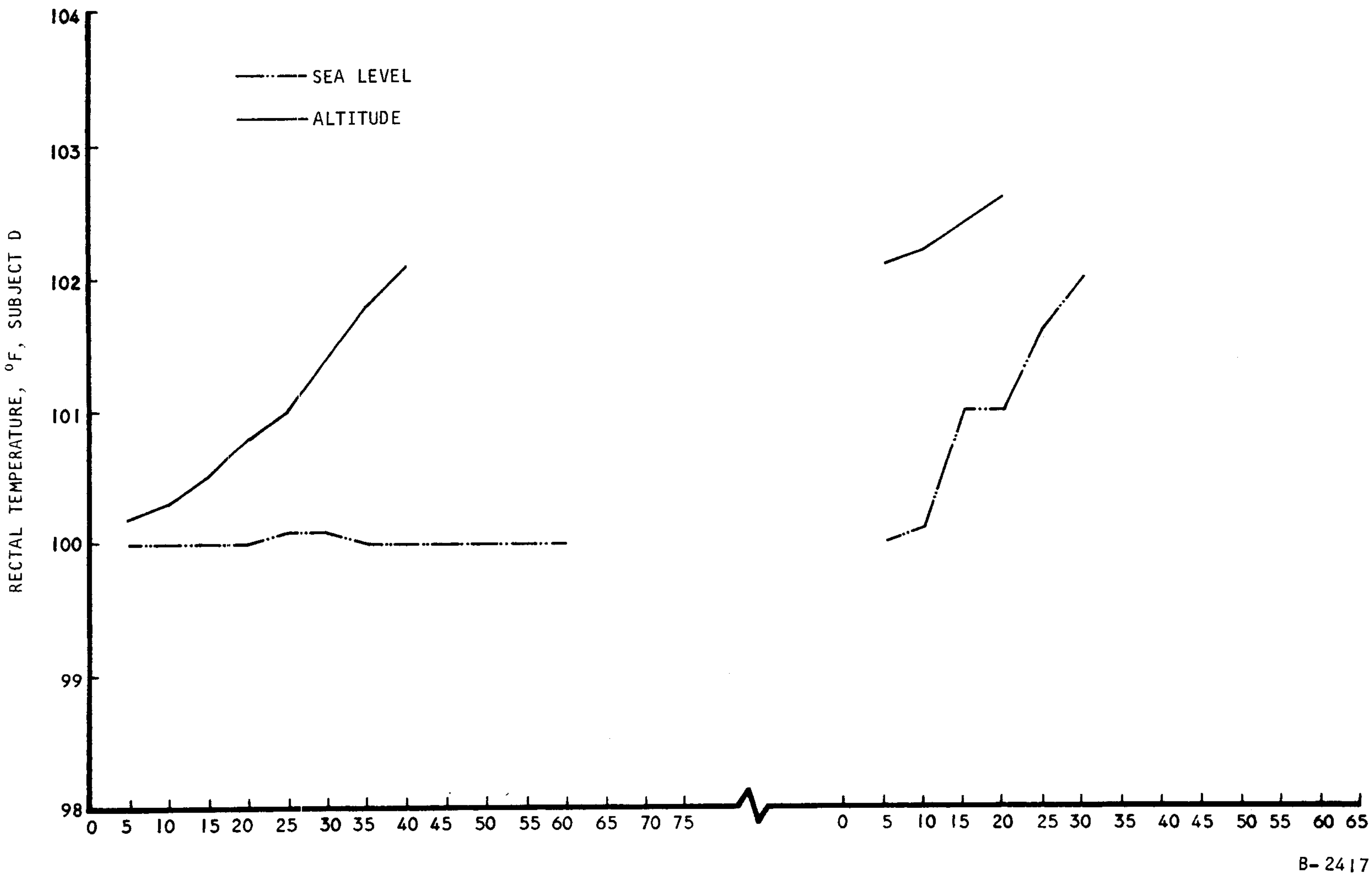


Figure 75. Rectal Temperature, Subject D

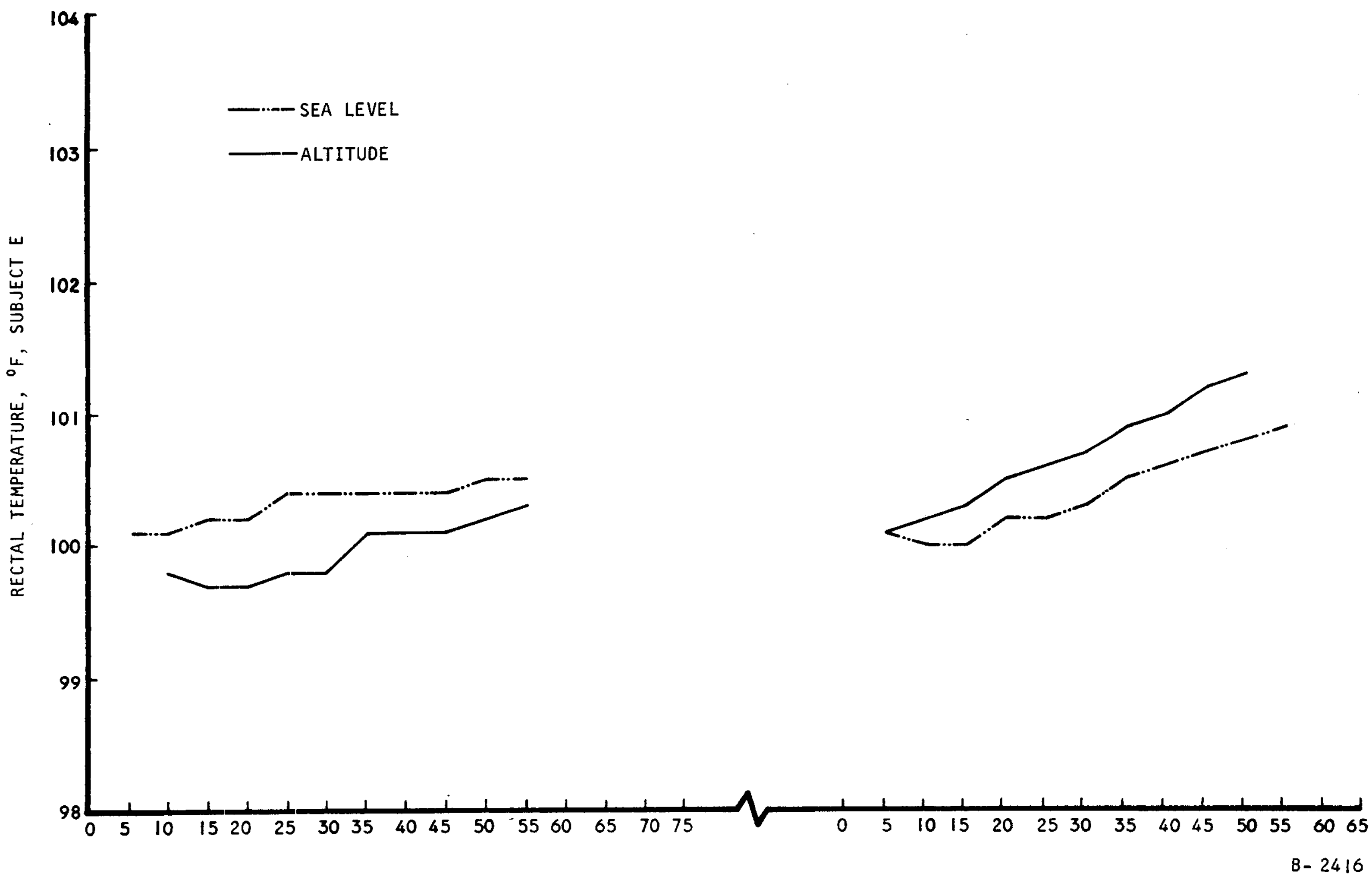


Figure 76. Rectal Temperature, Subject E

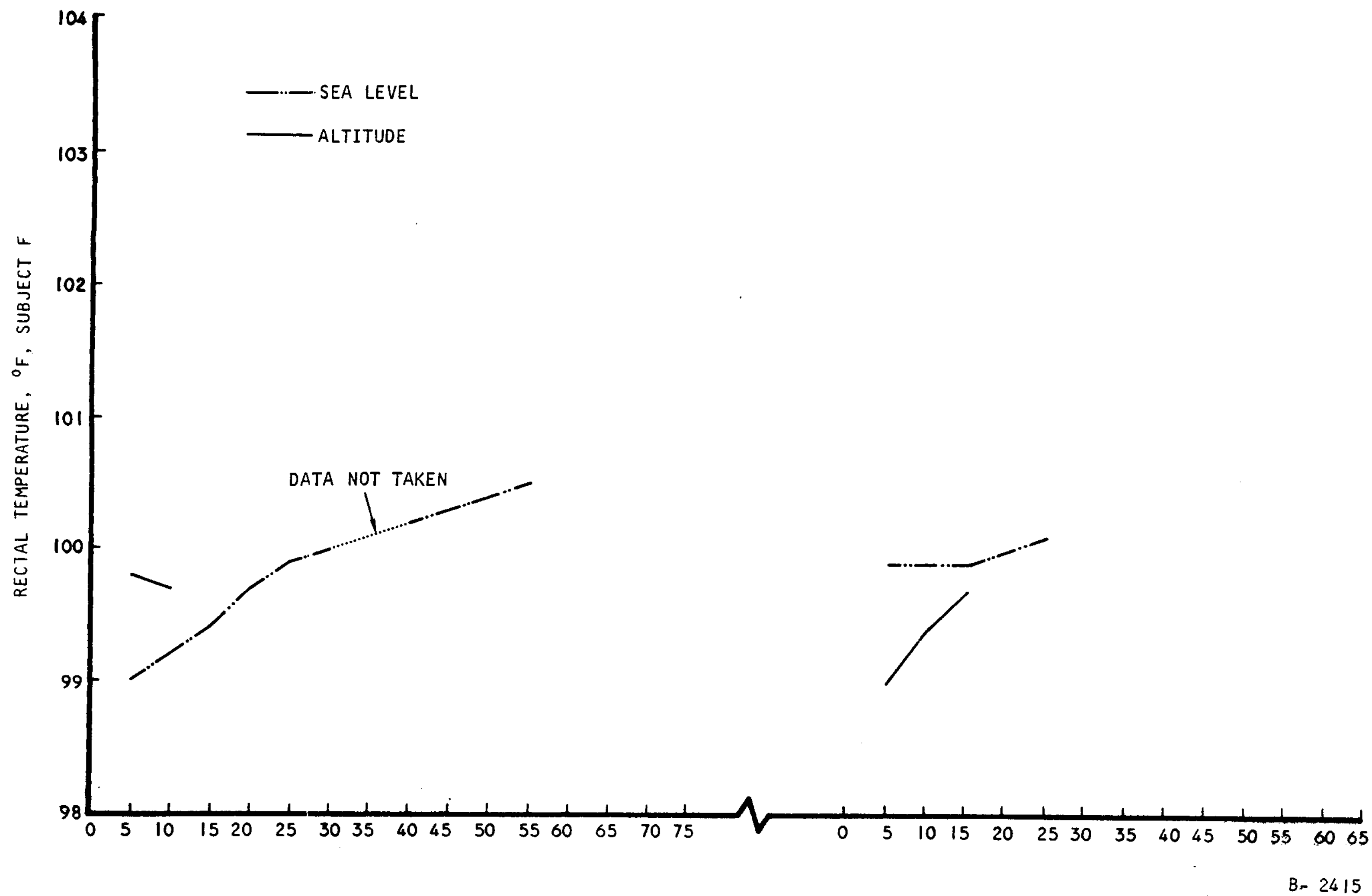


Figure 77. Rectal Temperature, Subject F

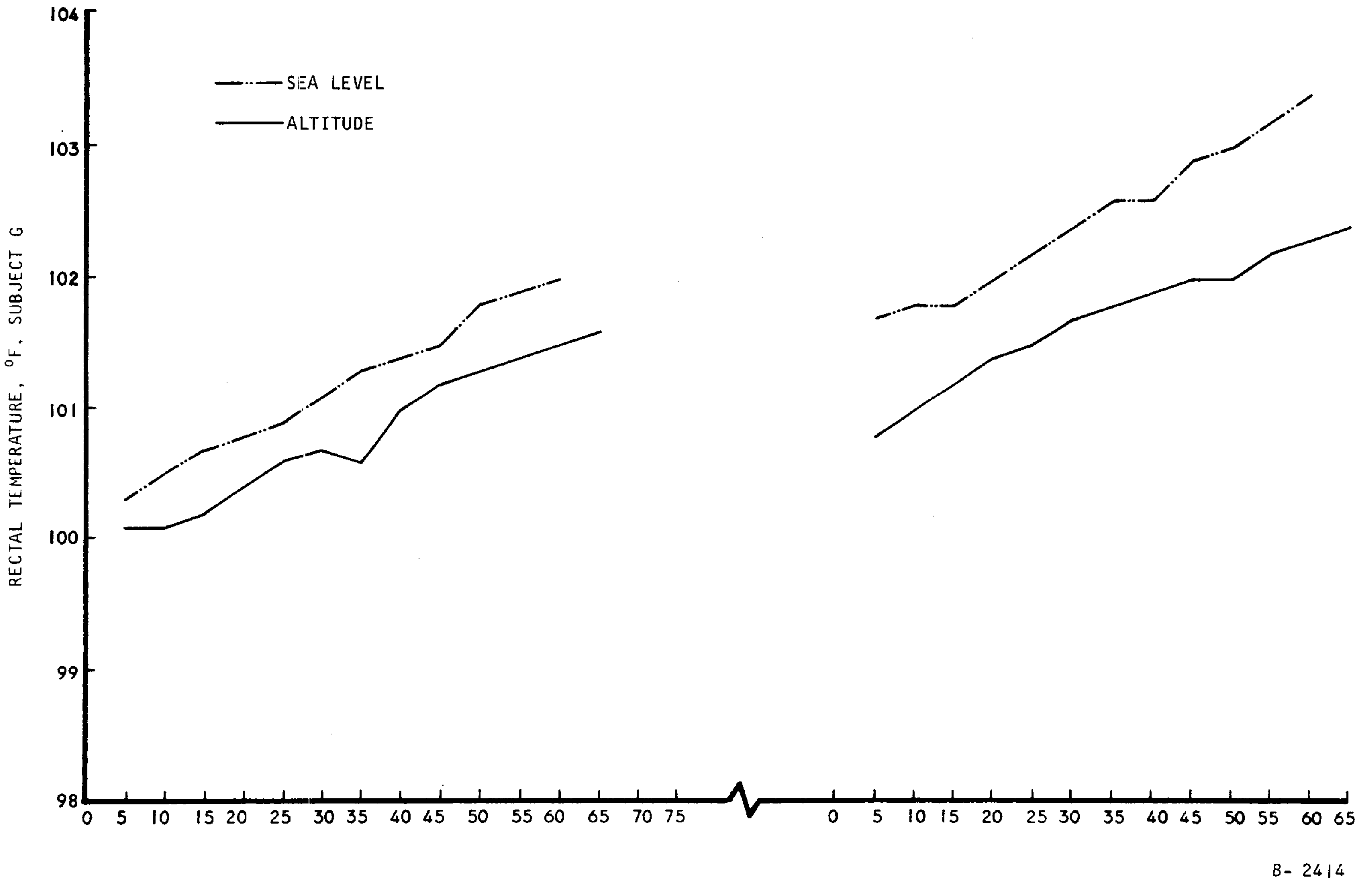


Figure 78. Rectal Temperature, Subject G

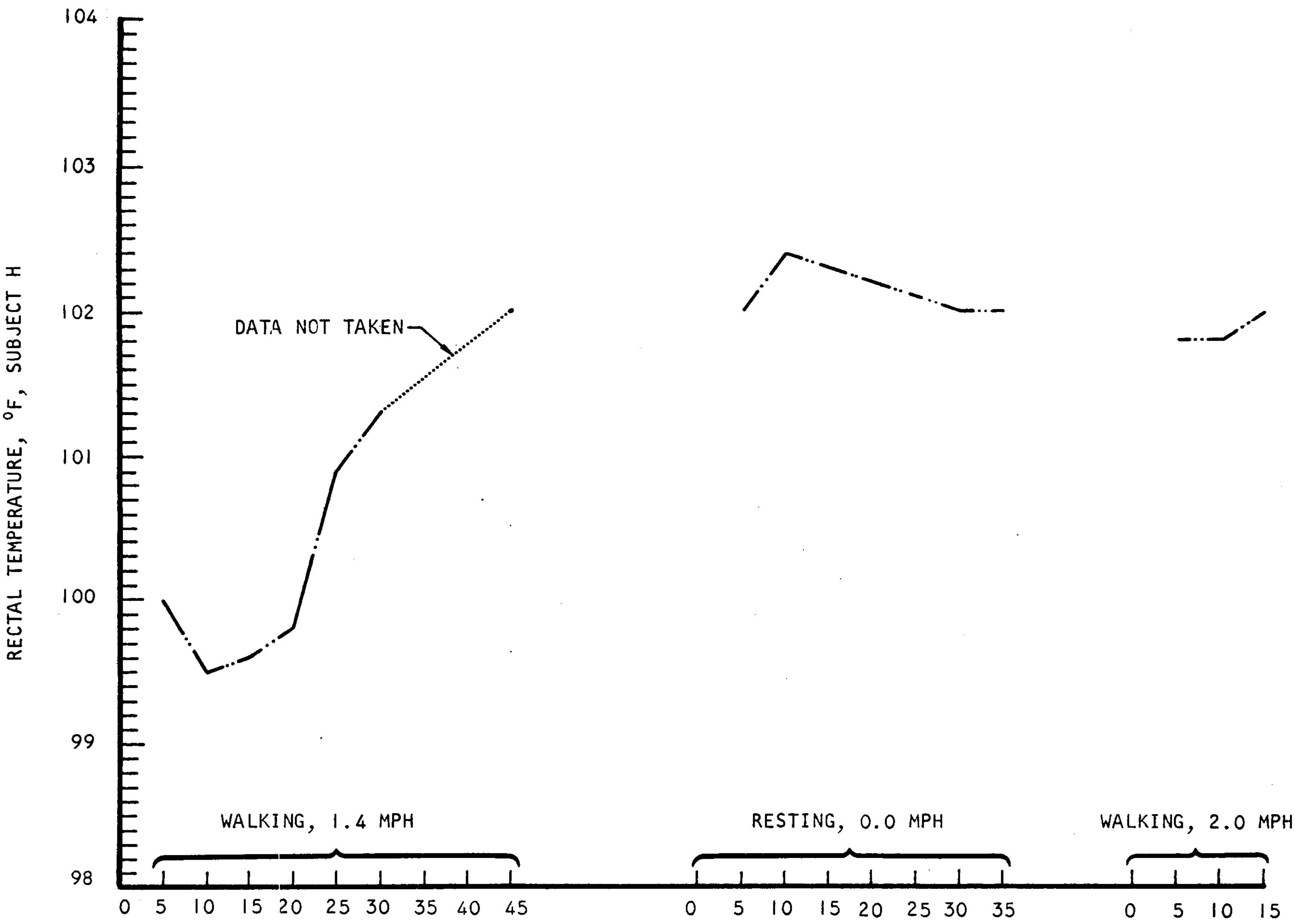


Figure 79. Rectal Temperature, Subject H

A-9156

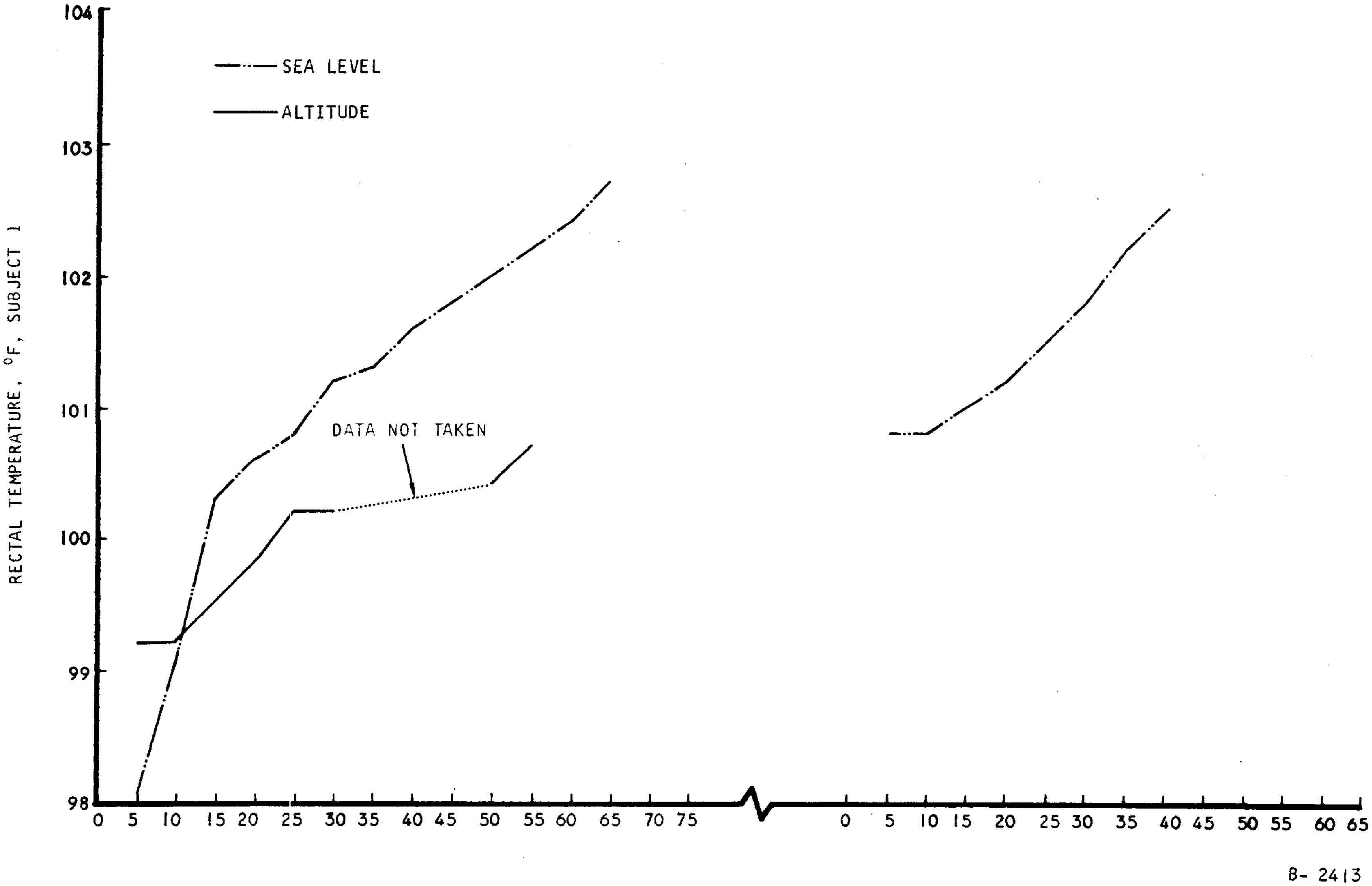
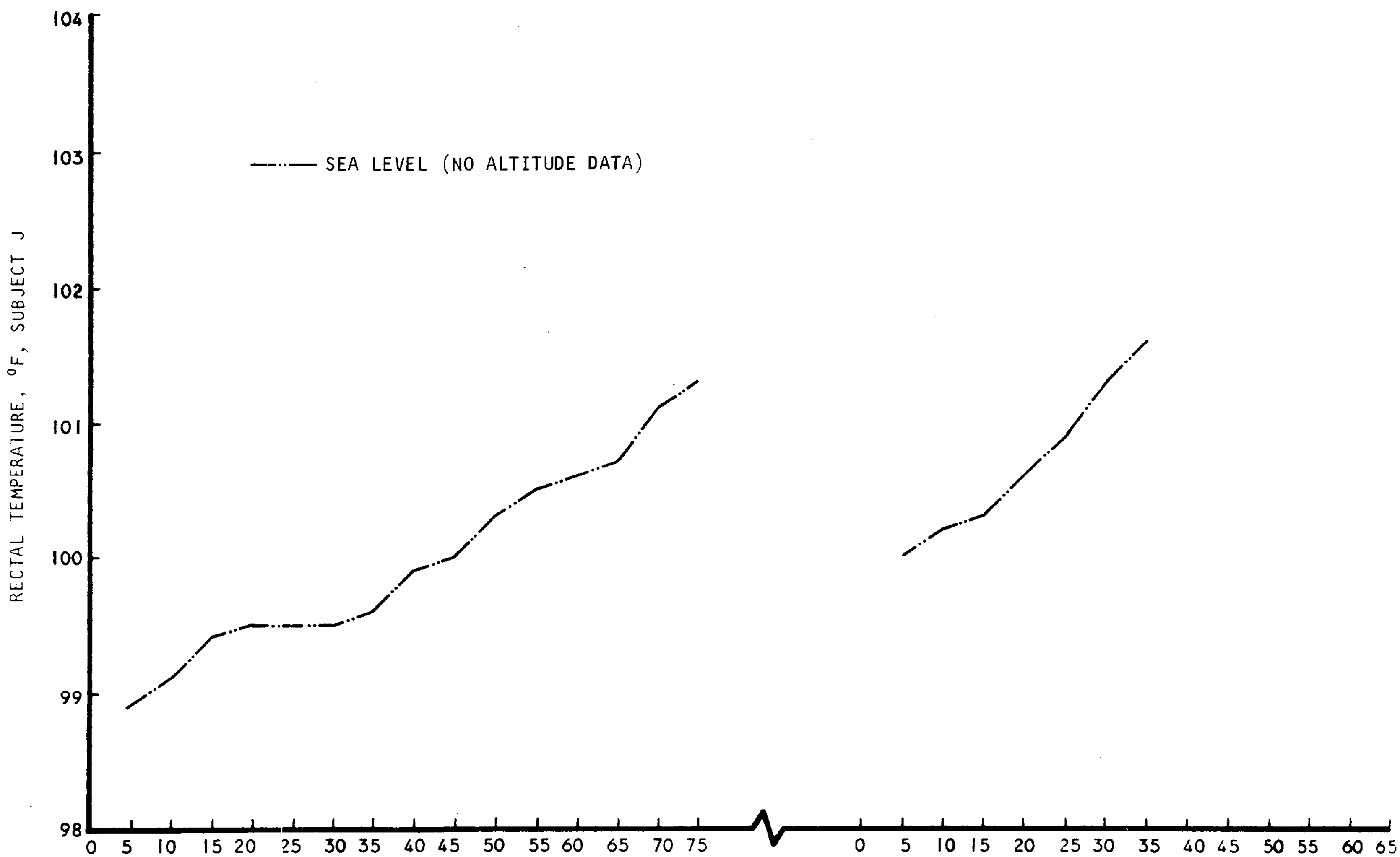


Figure 80. Rectal Temperature, Subject I



5-2412

Figure 81. Rectal Temperature, Subject J

AVERAGE SKIN TEMPERATURE

The graphs of the average skin temperature of the subjects (Figures 82 through 91) clearly show the generally lower skin temperatures that occurred at altitude conditions. These skin temperatures were calculated as previously described. They are presented for altitude and sea level conditions, as well as for high and low exercise levels; the latter are depicted at the right and left, respectively, of each graph.

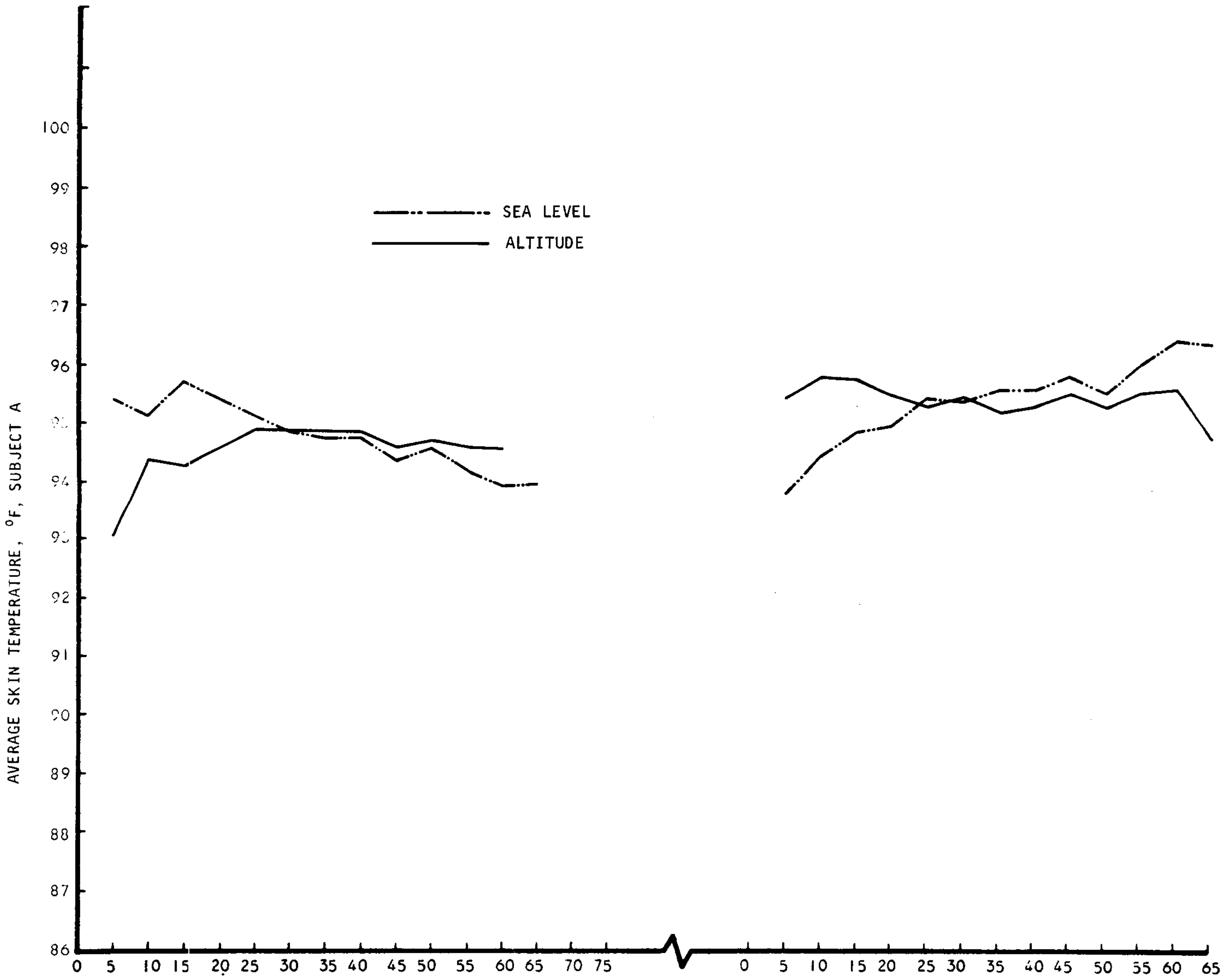


Figure 82. Average Skin Temperature, Subject A

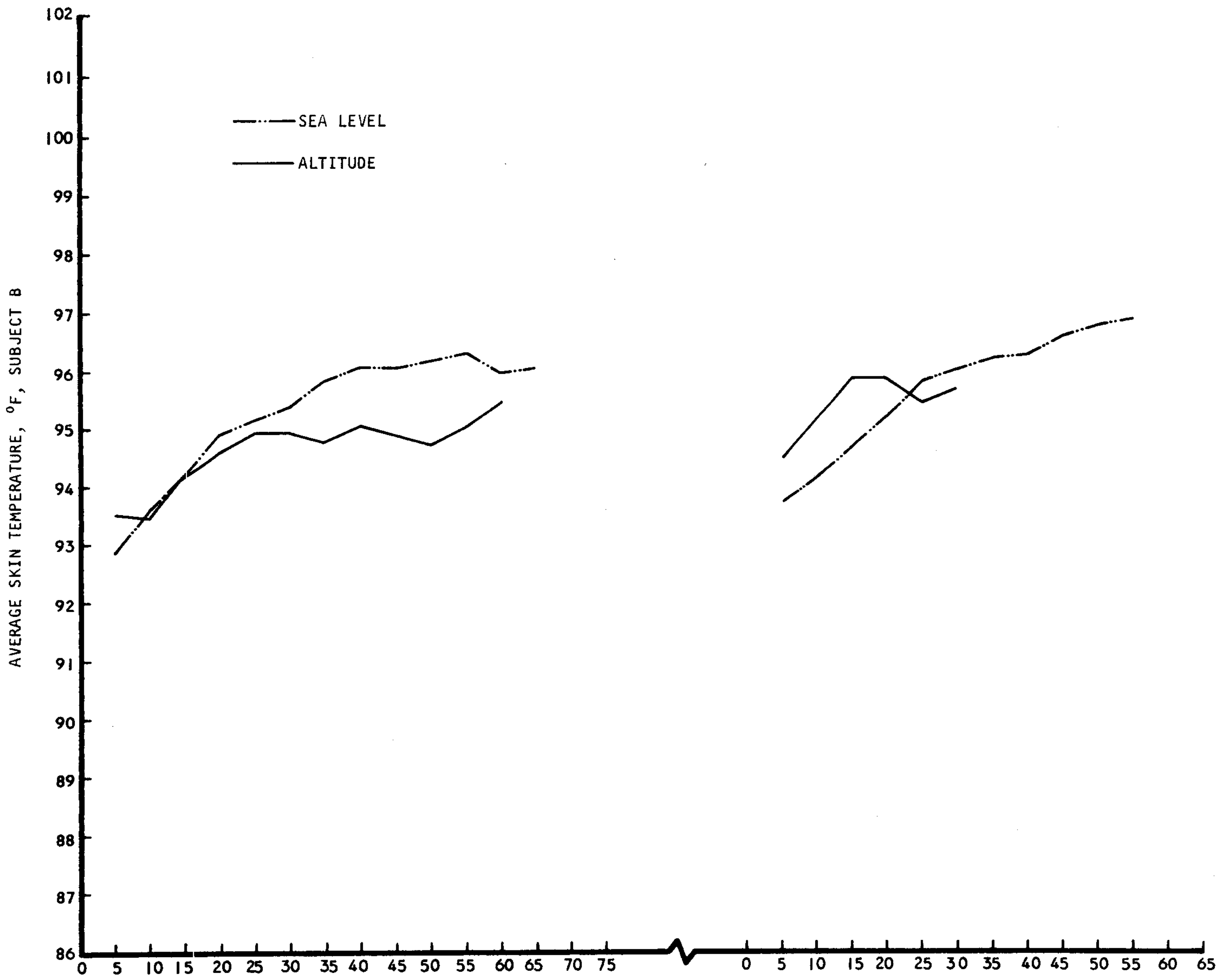


Figure 83. Average Skin Temperature, Subject B

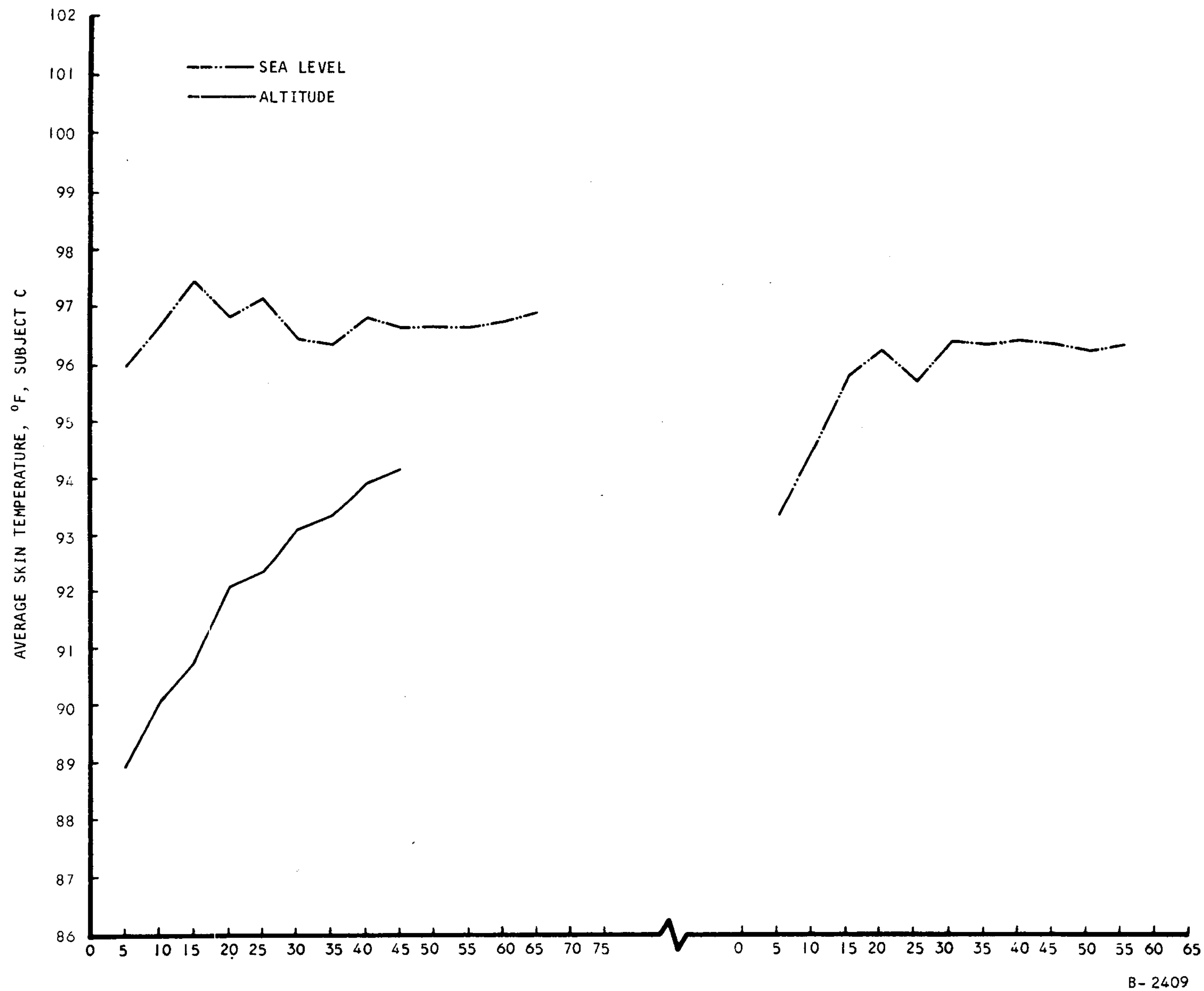


Figure 84. Average Skin Temperature, Subject C

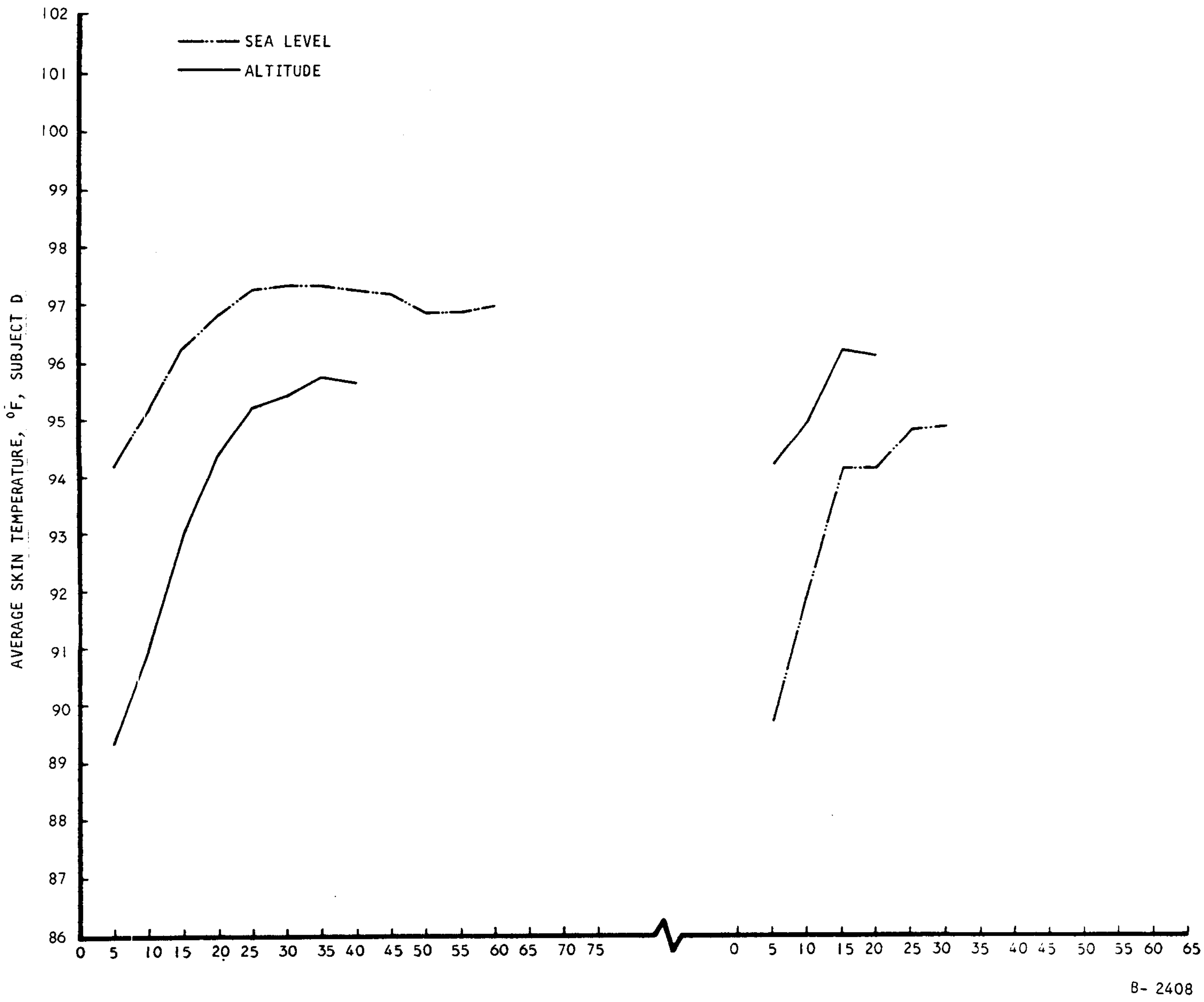


Figure 85. Average Skin Temperature, Subject D

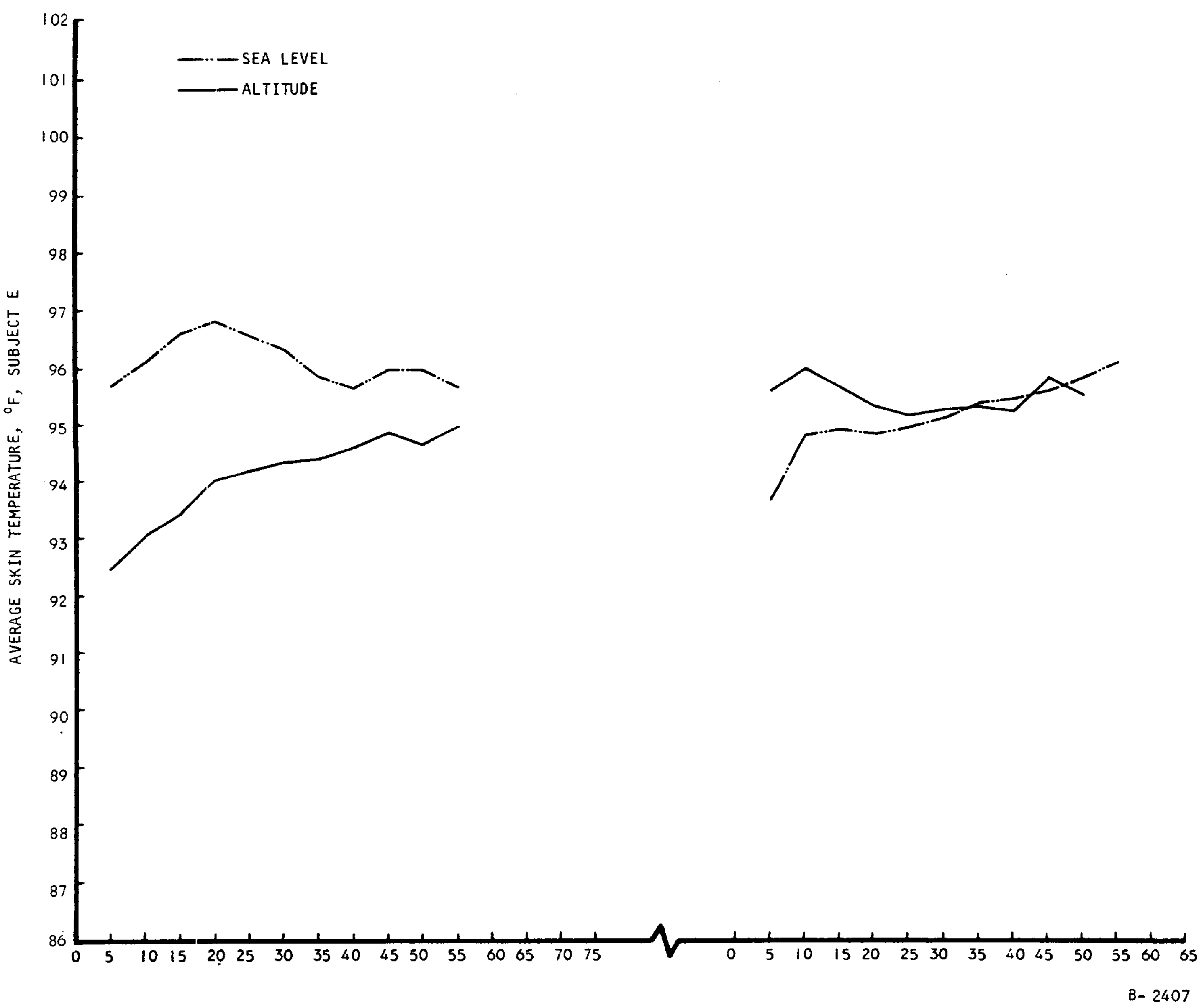


Figure 86. Average Skin Temperature, Subject E

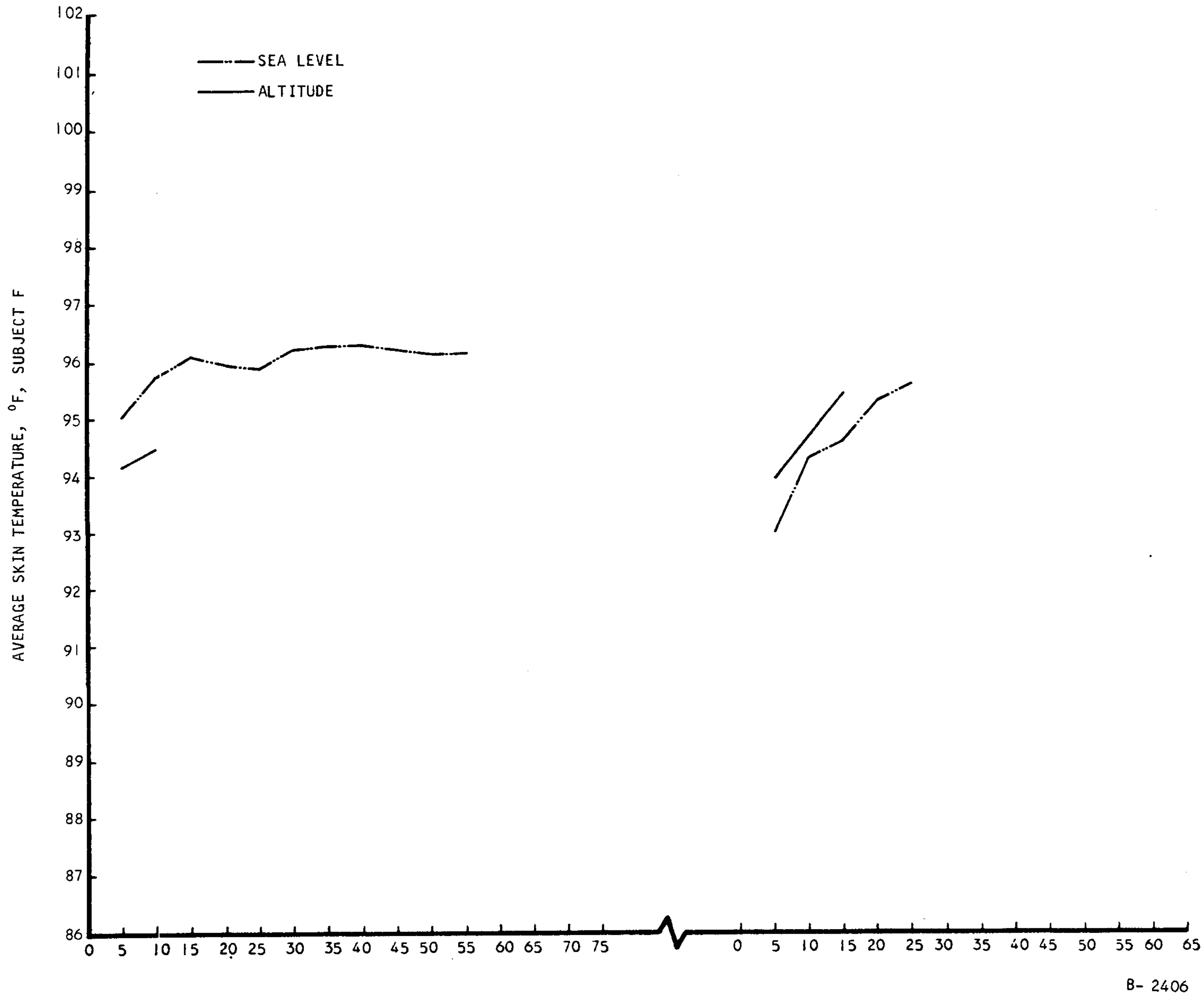


Figure 87. Average Skin Temperature, Subject F

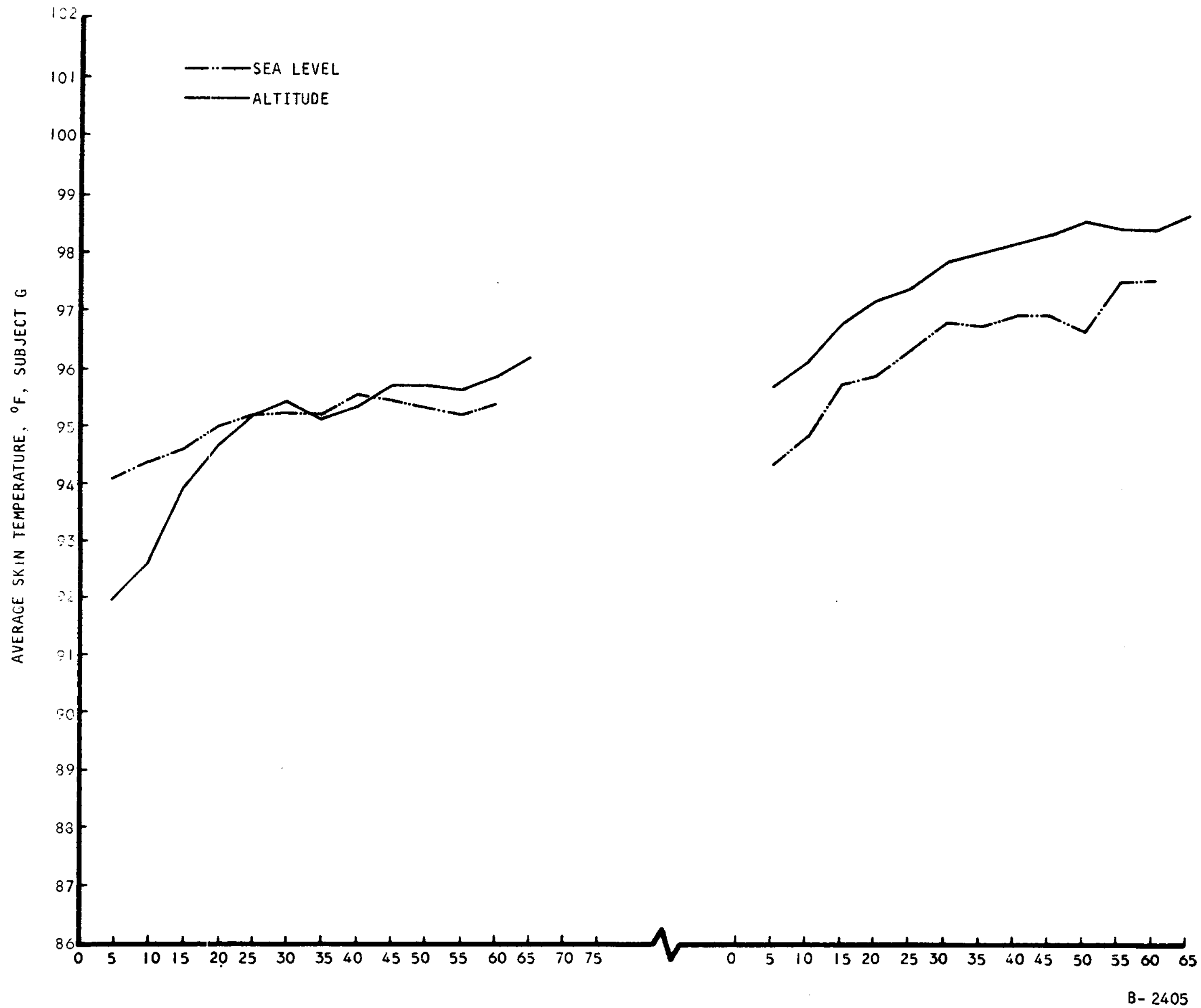


Figure 88. Average Skin Temperature, Subject G

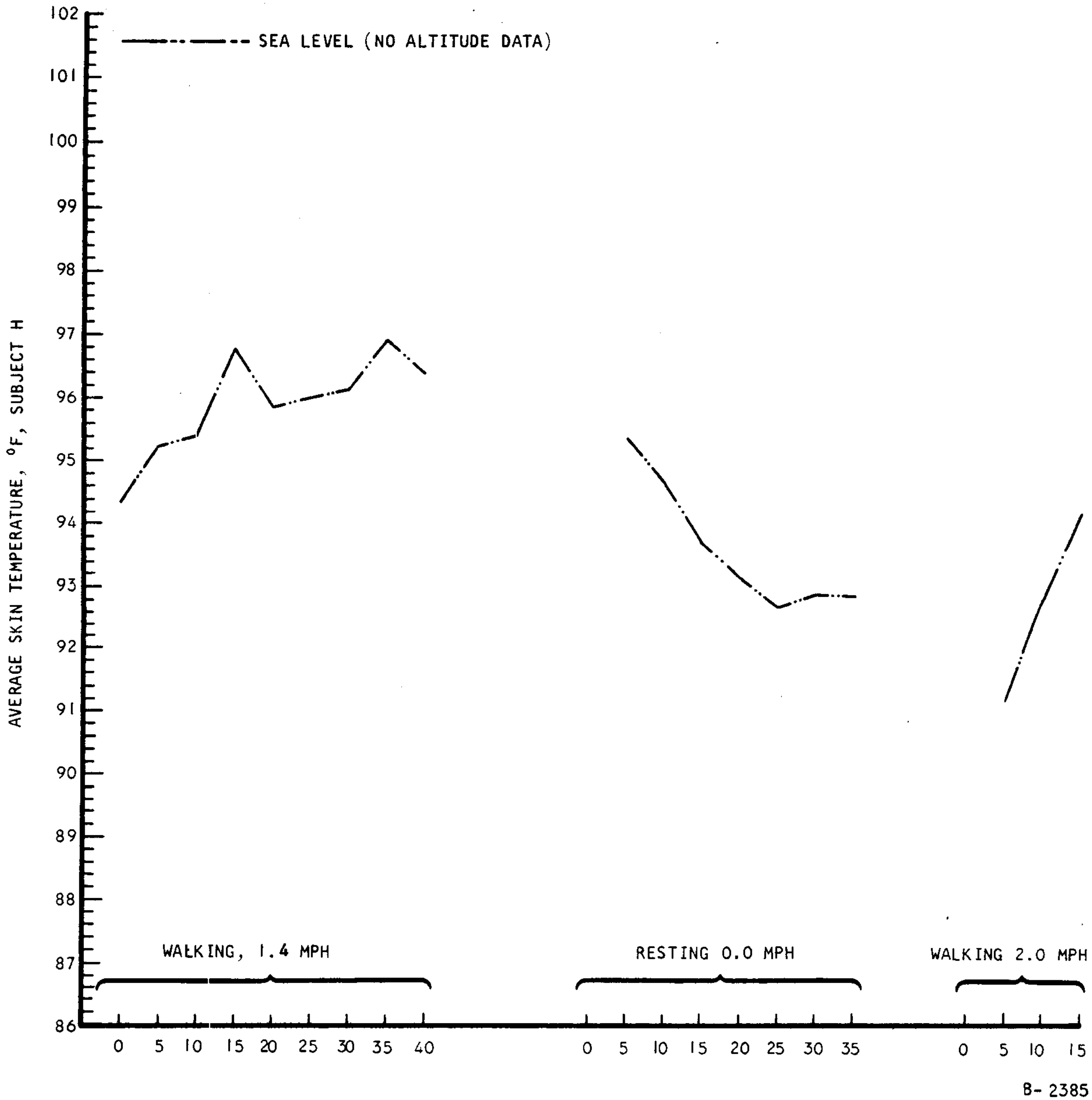


Figure 89. Average Skin Temperature, Subject H

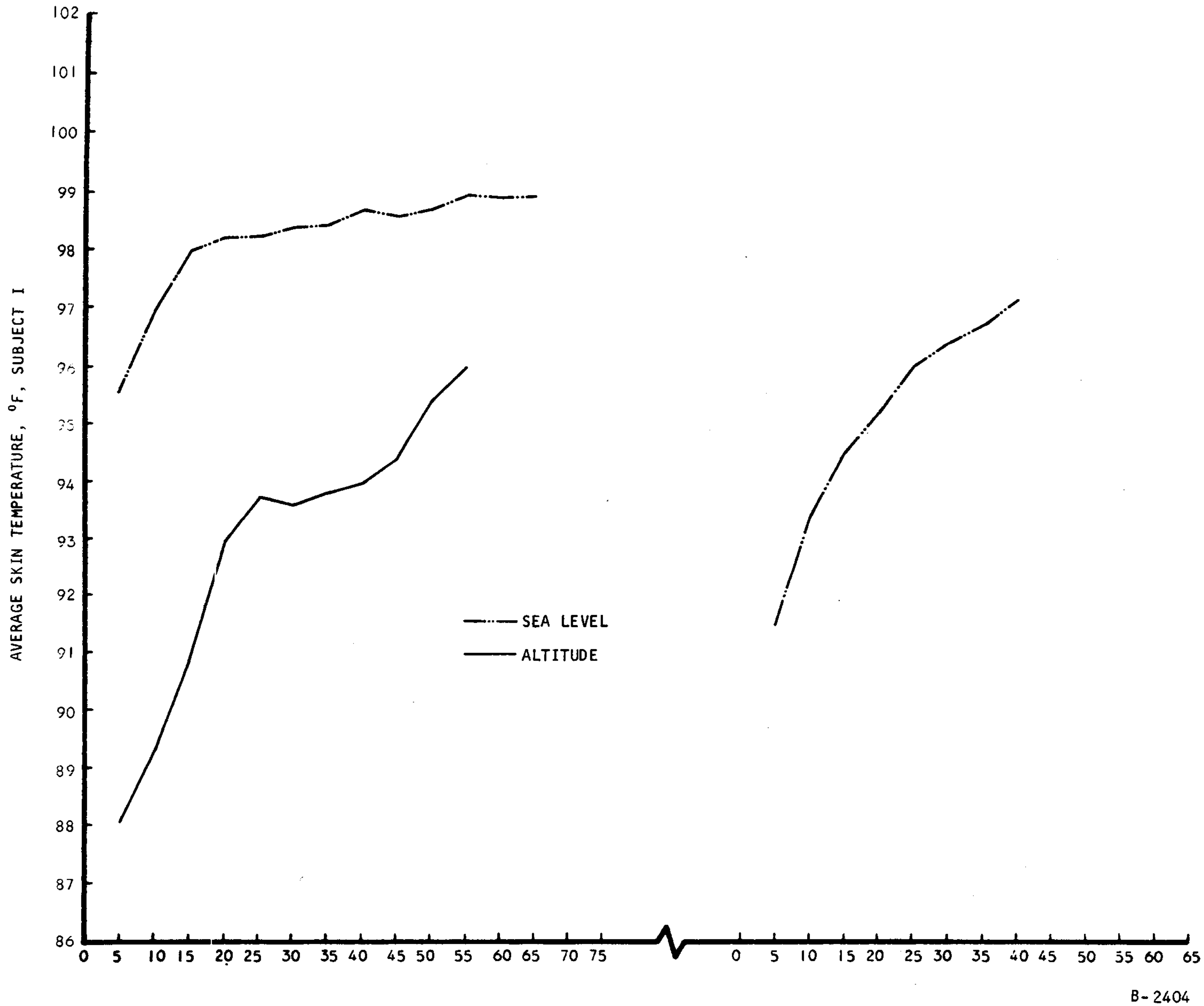


Figure 90. Average Skin Temperature, Subject I

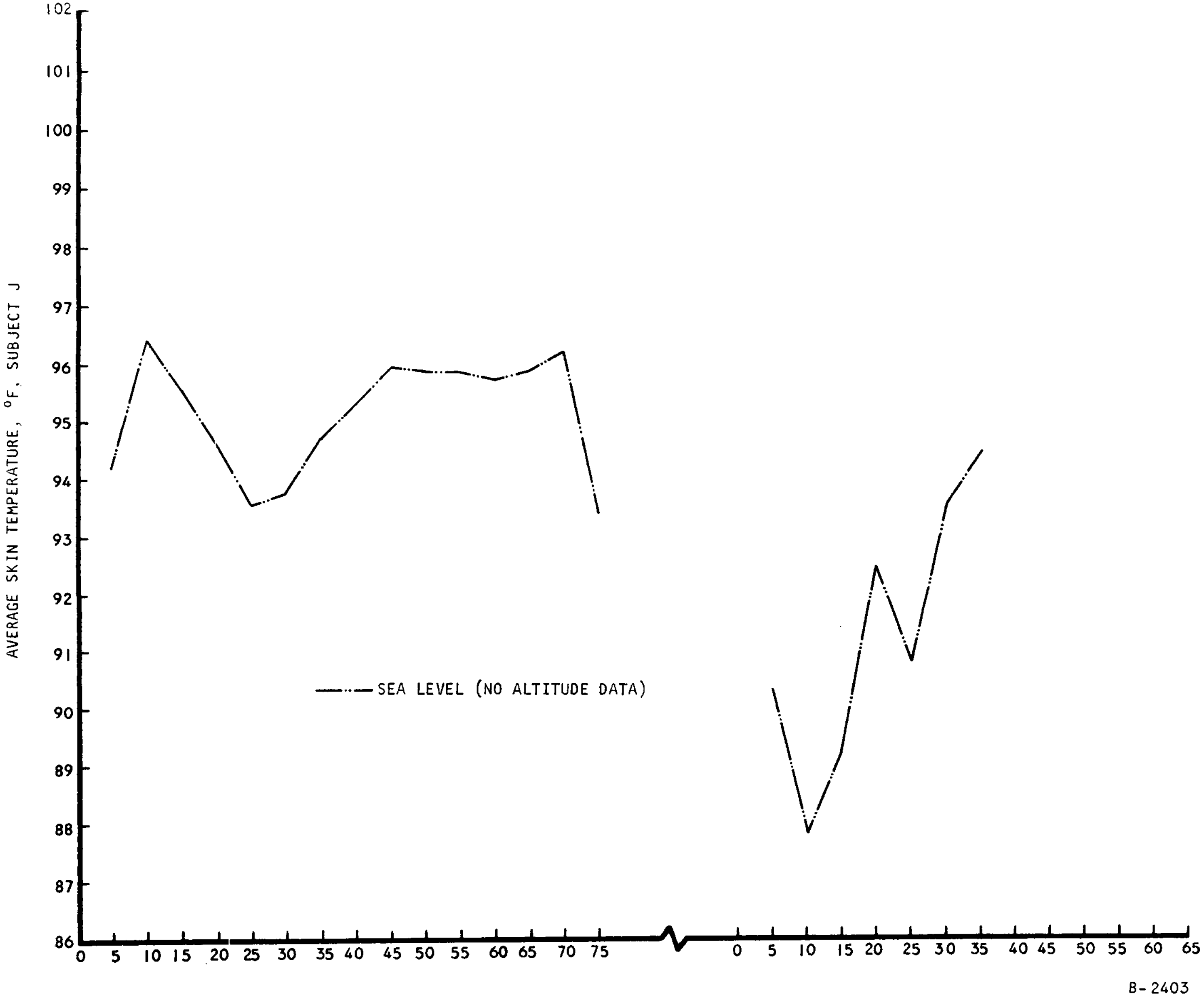


Figure 91. Average Skin Temperature, Subject J

MEAN BODY TEMPERATURE

Mean body temperatures were calculated for each 5-min period for every test by the method previously described. Figures 92 through 101 present the results of these calculations for low and high activity levels (on the left and right of each graph, respectively).

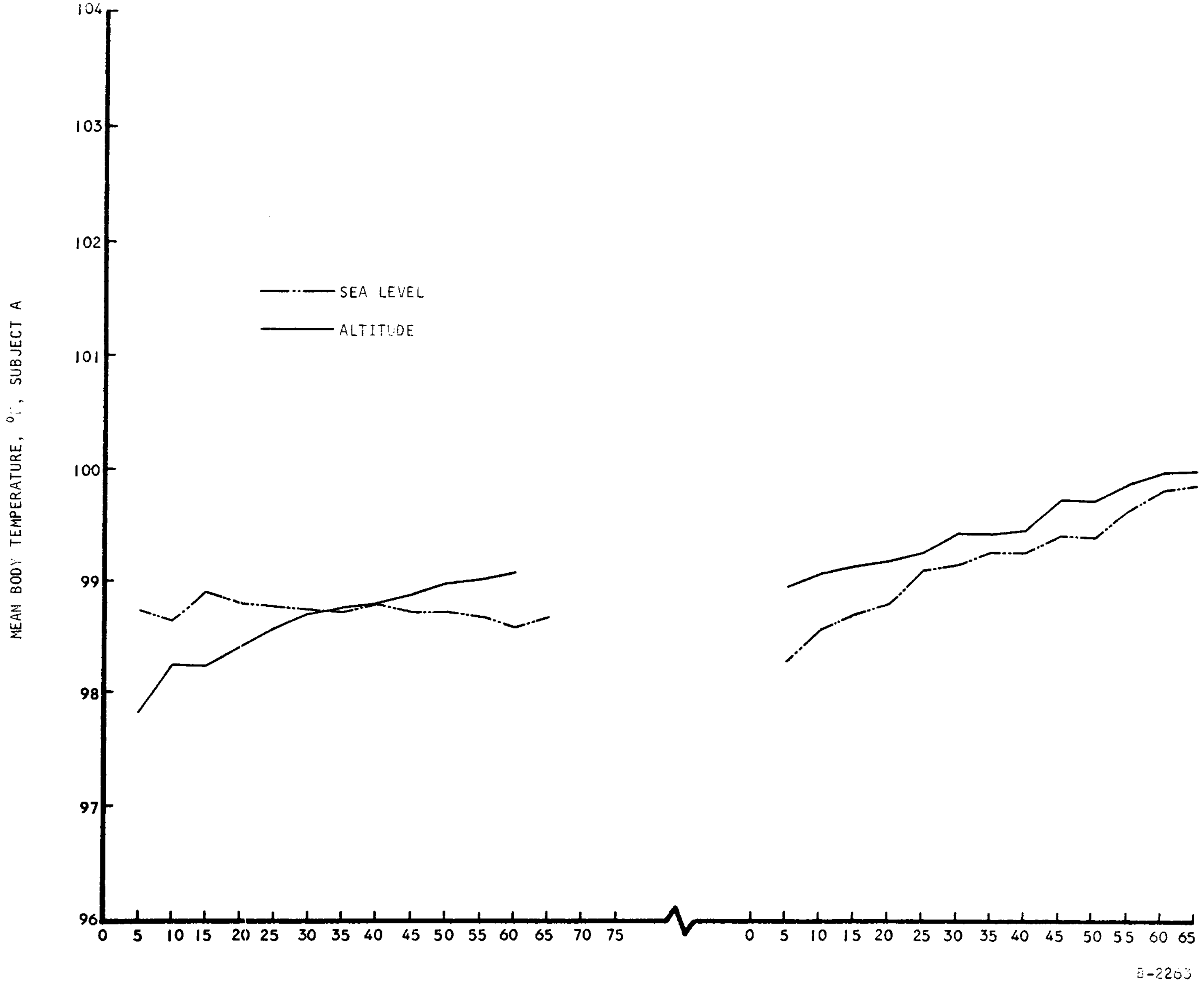


Figure 92. Mean Body Temperature, Subject A

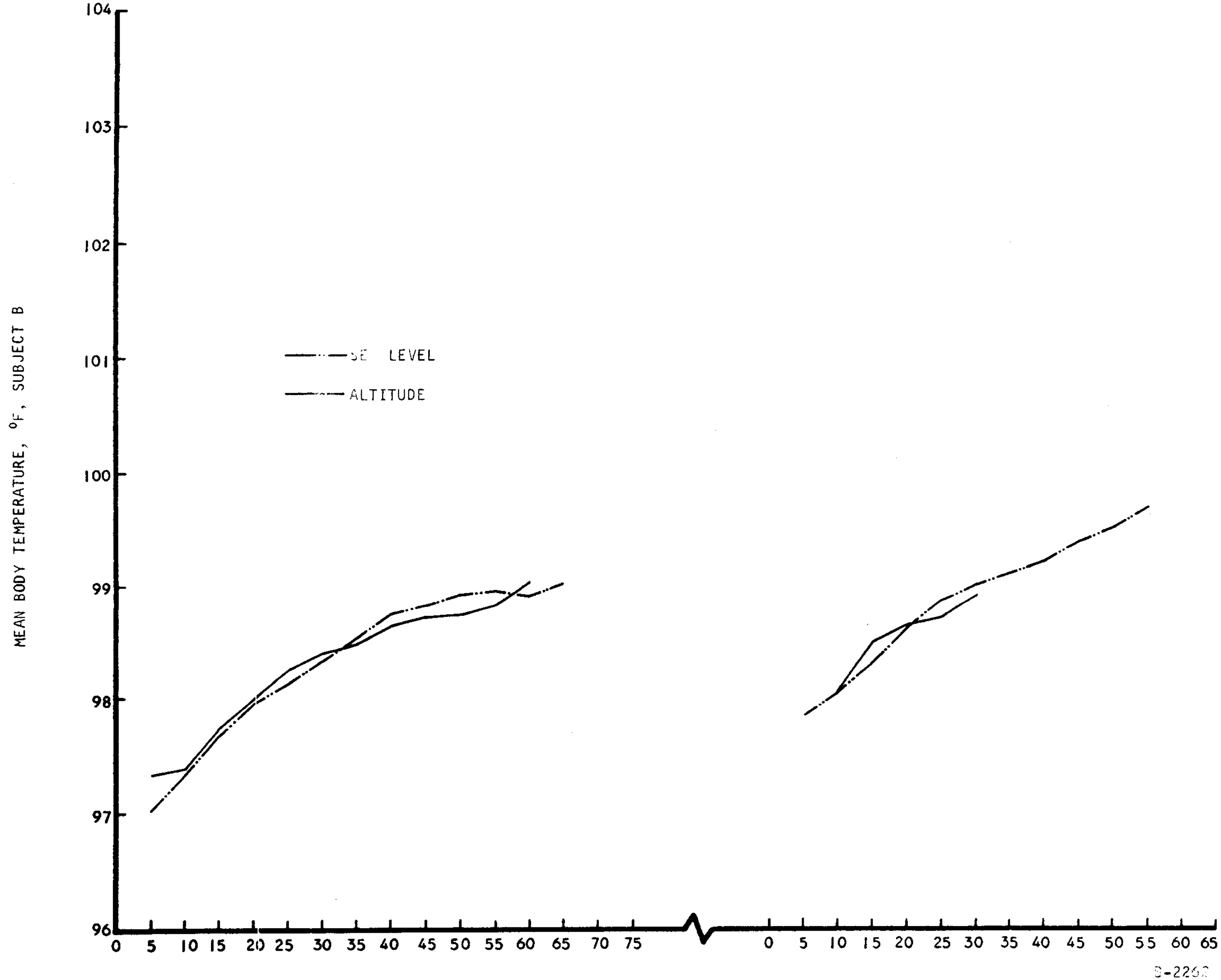


Figure 93. Mean Body Temperature, Subject B

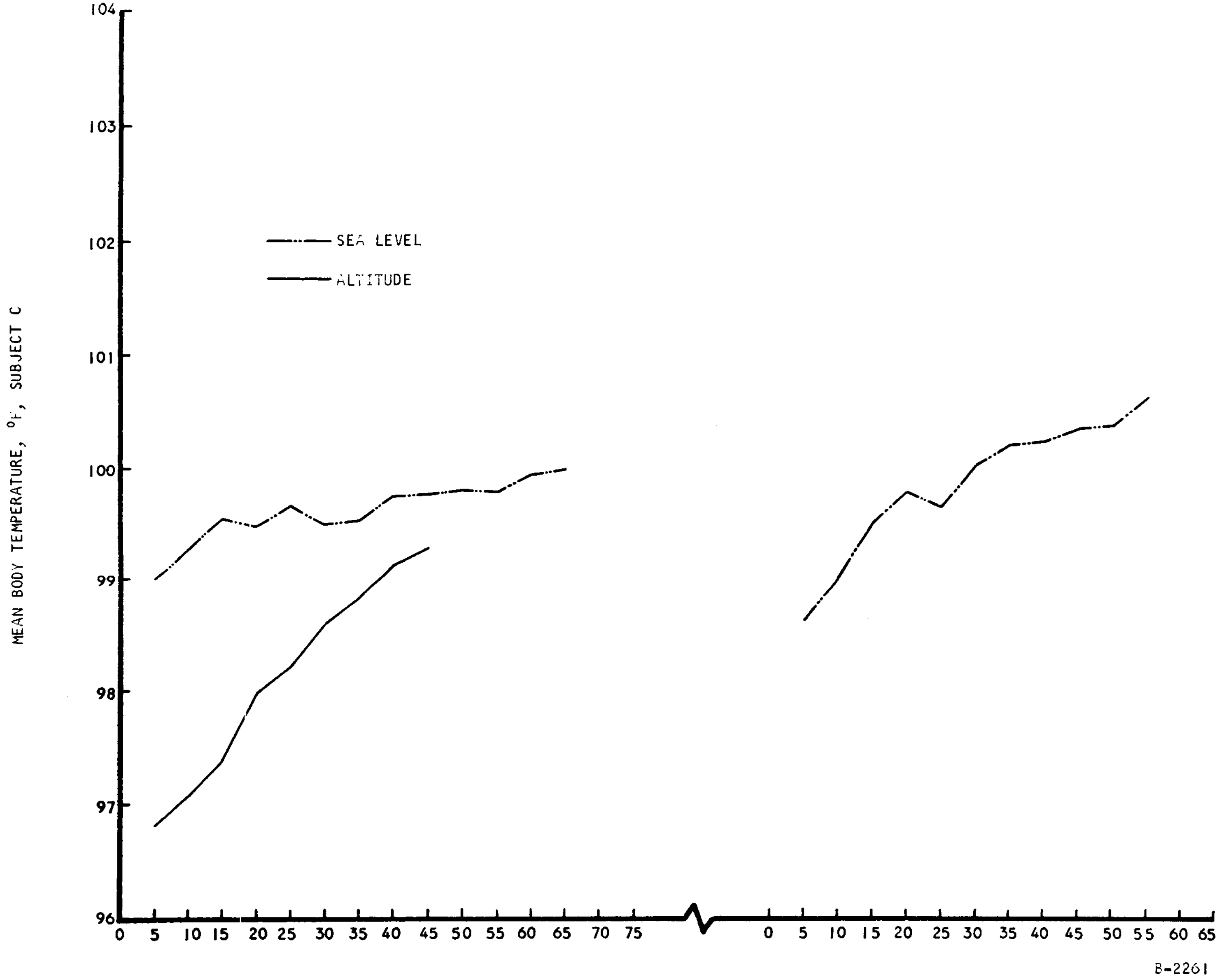


Figure 94. Mean Body Temperature, Subject C

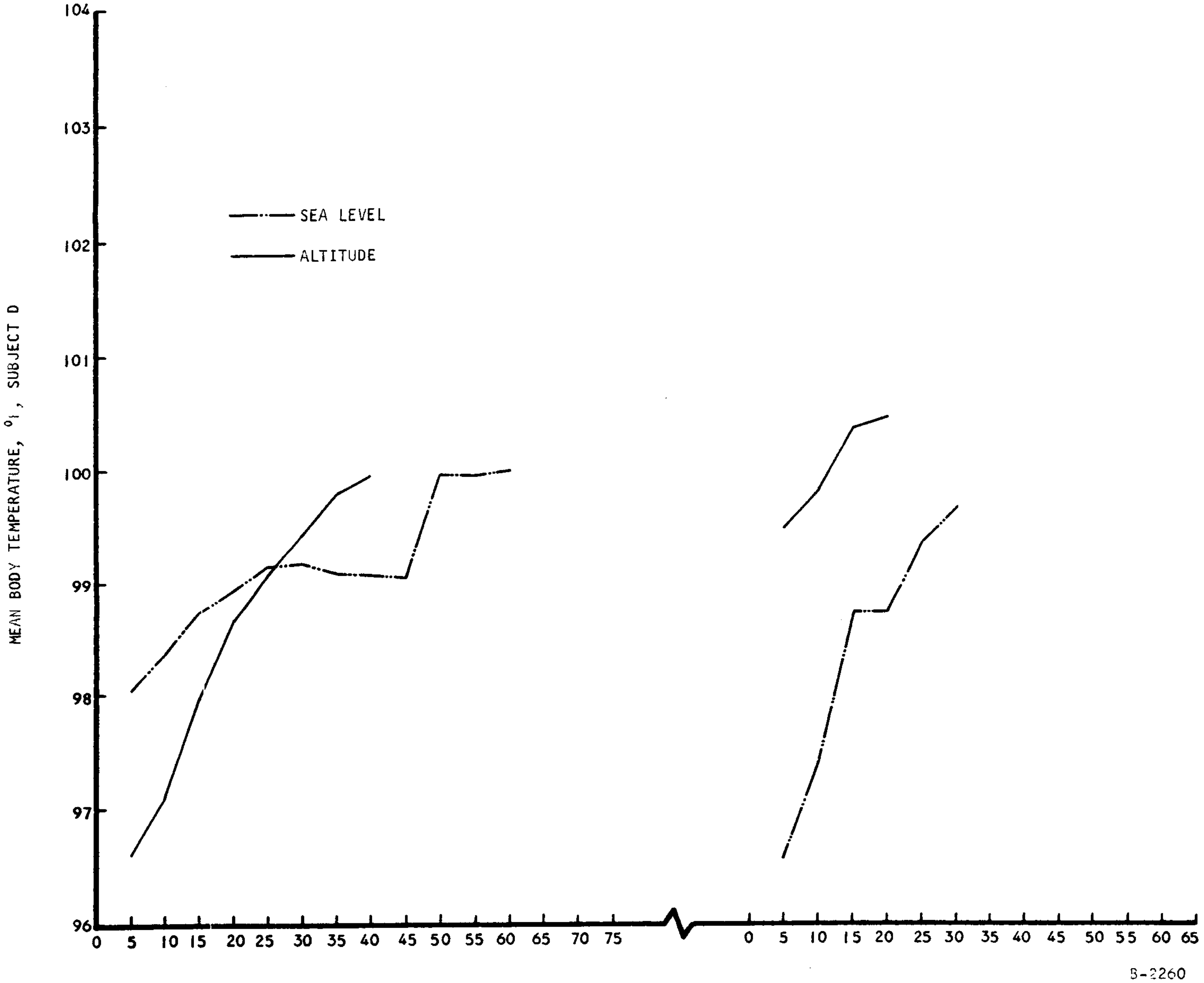


Figure 95. Mean Body Temperature, Subject D

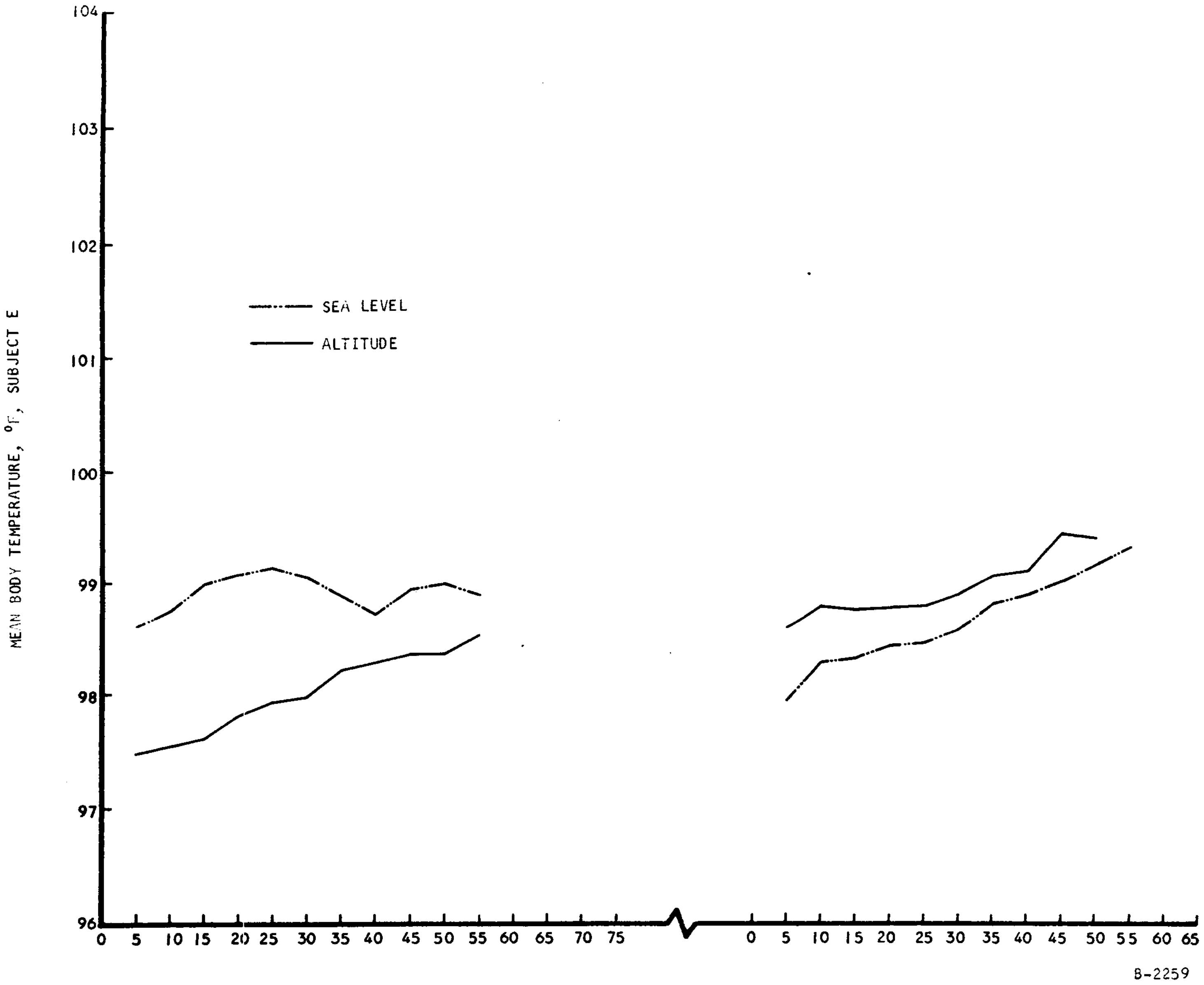


Figure 96. Mean Body Temperature, Subject E

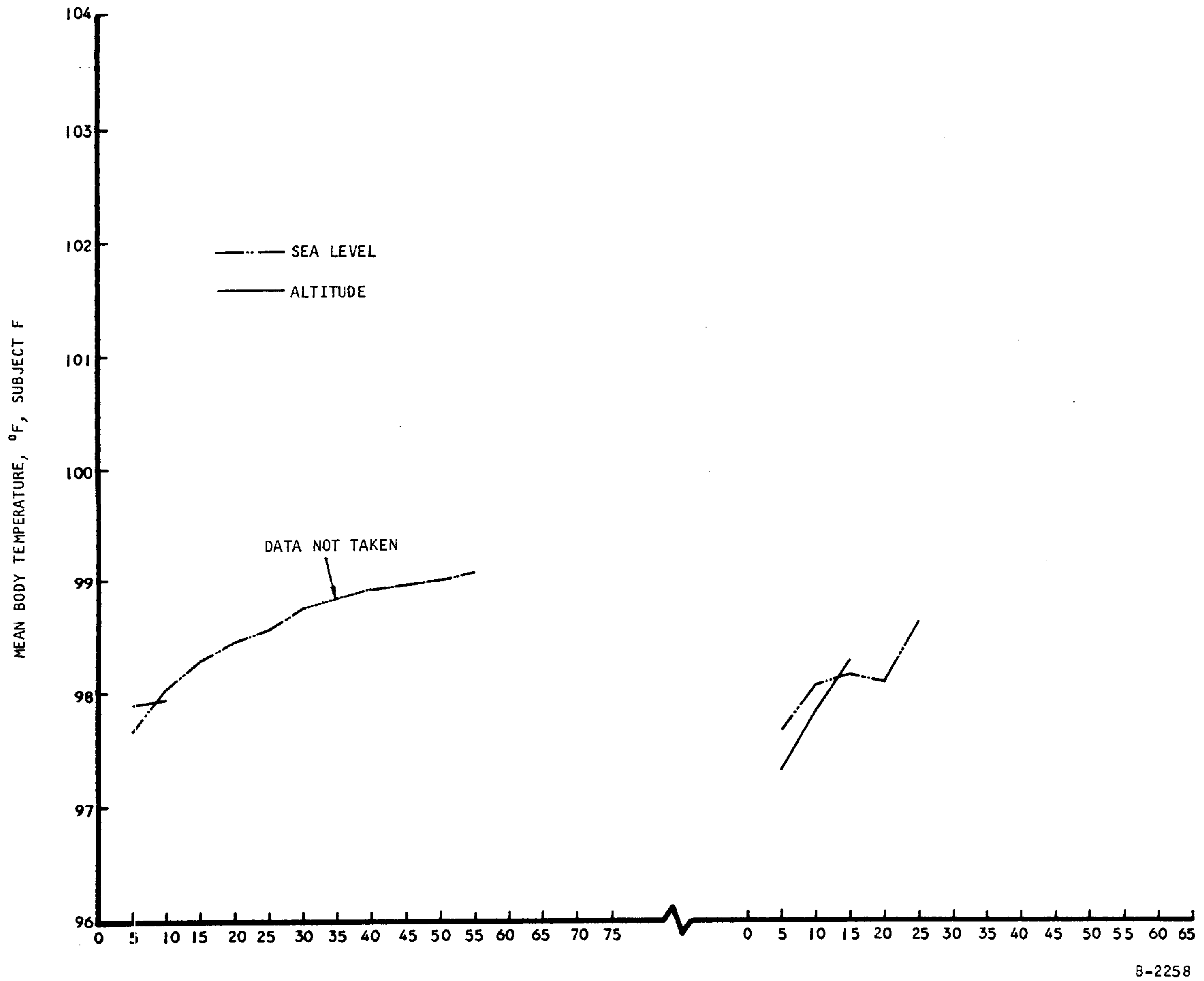


Figure 97. Mean Body Temperature, Subject F

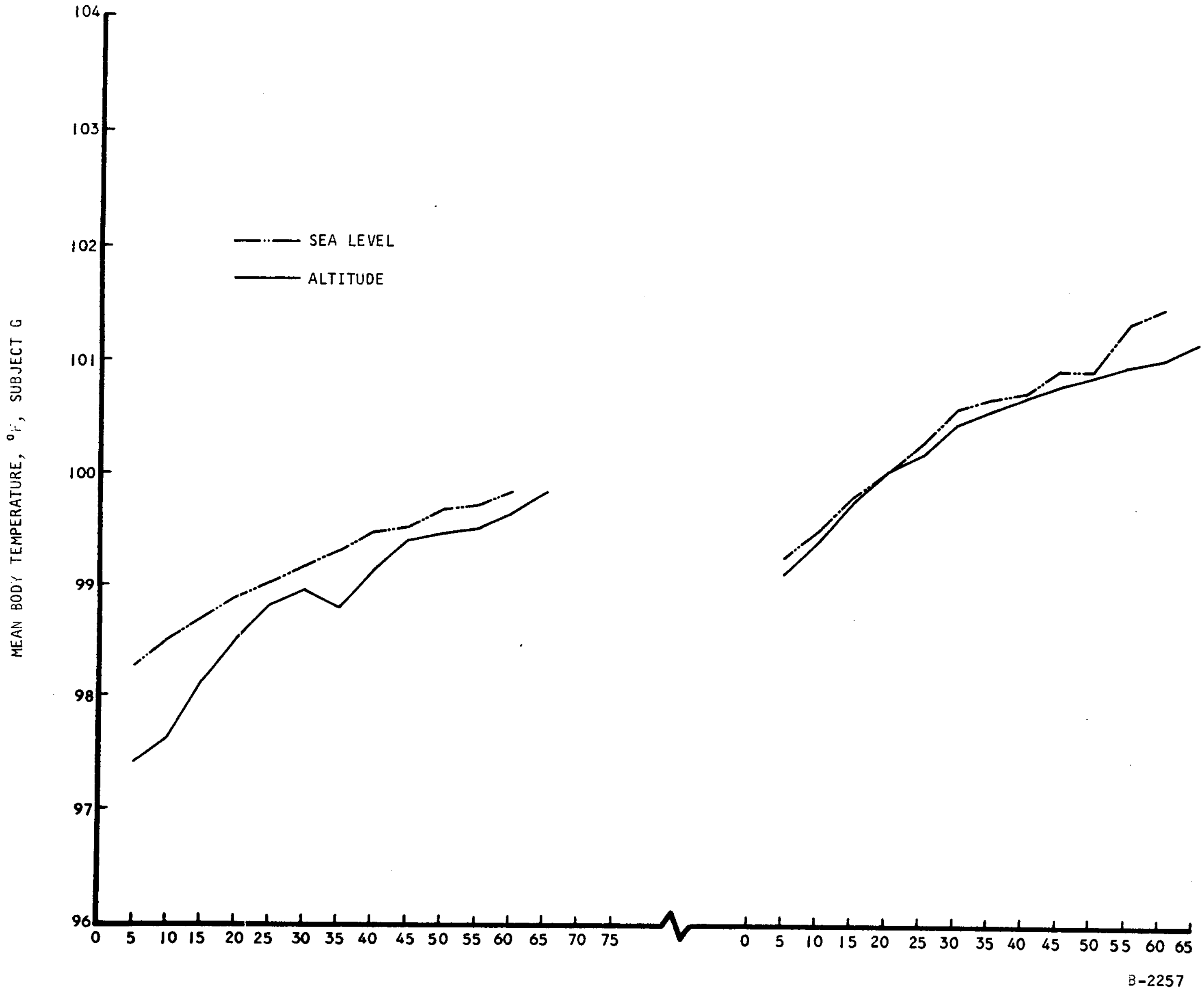


Figure 98. Mean Body Temperature, Subject G

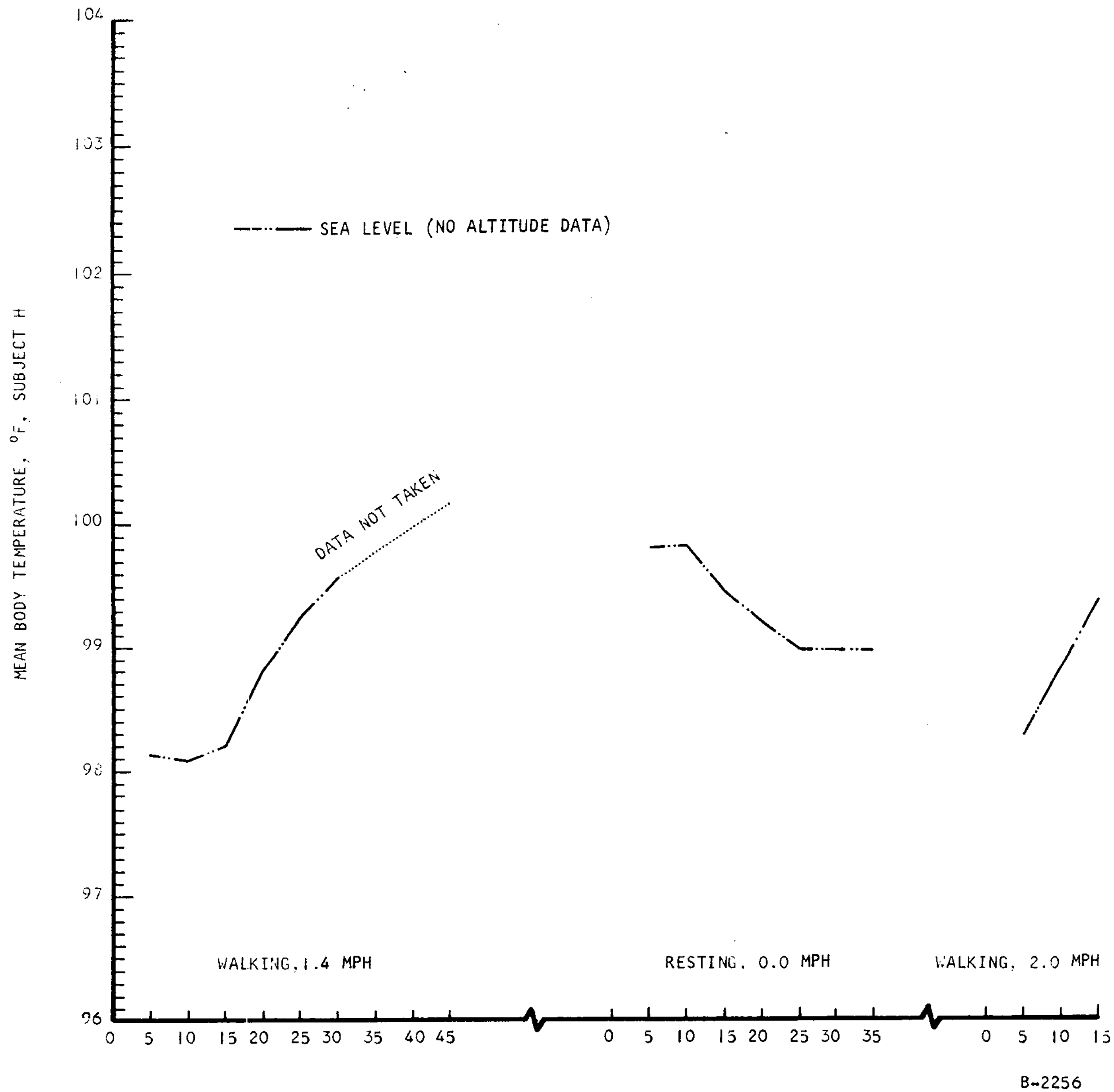
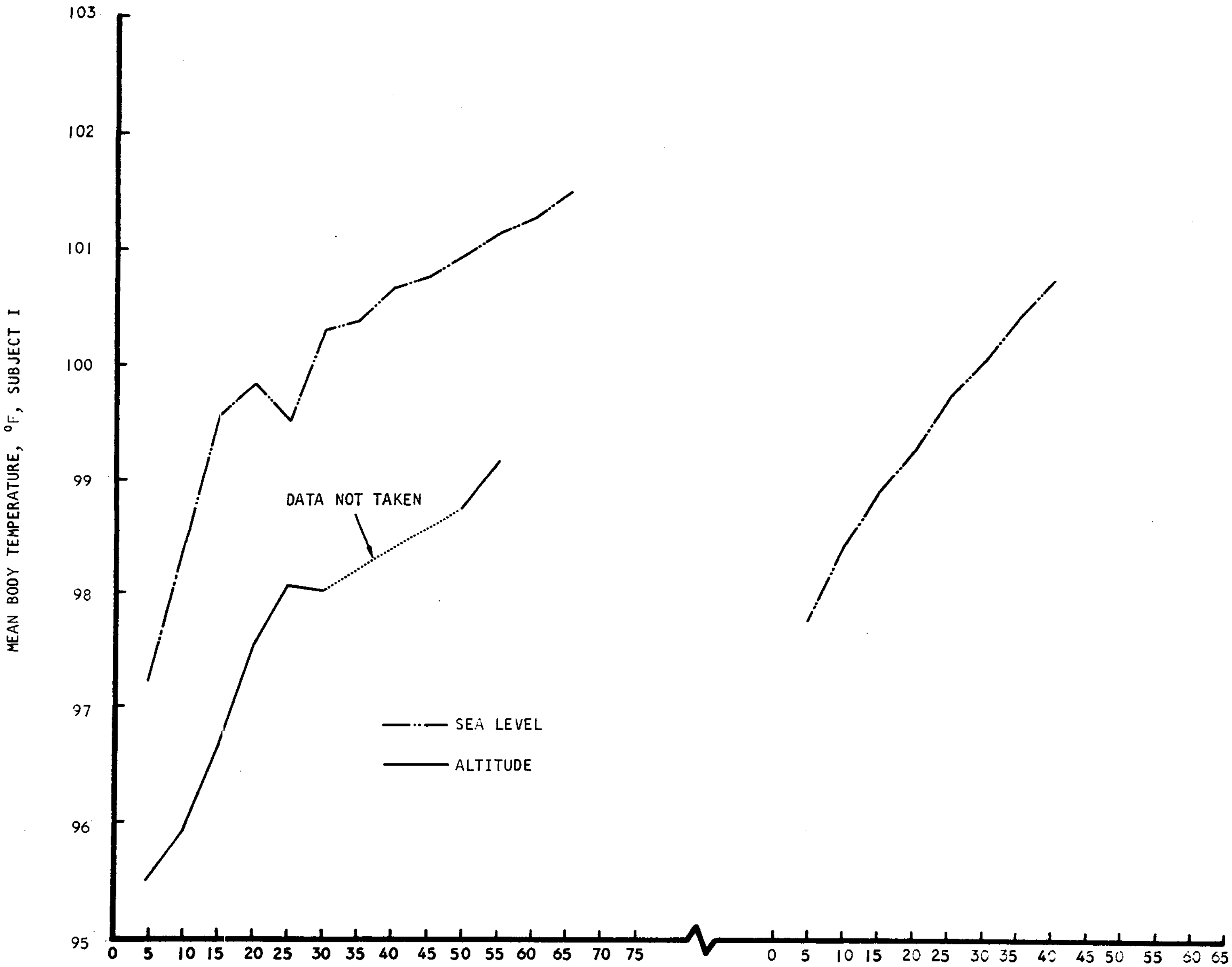


Figure 99. Mean Body Temperature, Subject H



B-2255

Figure 100. Mean Body Temperature, Subject I

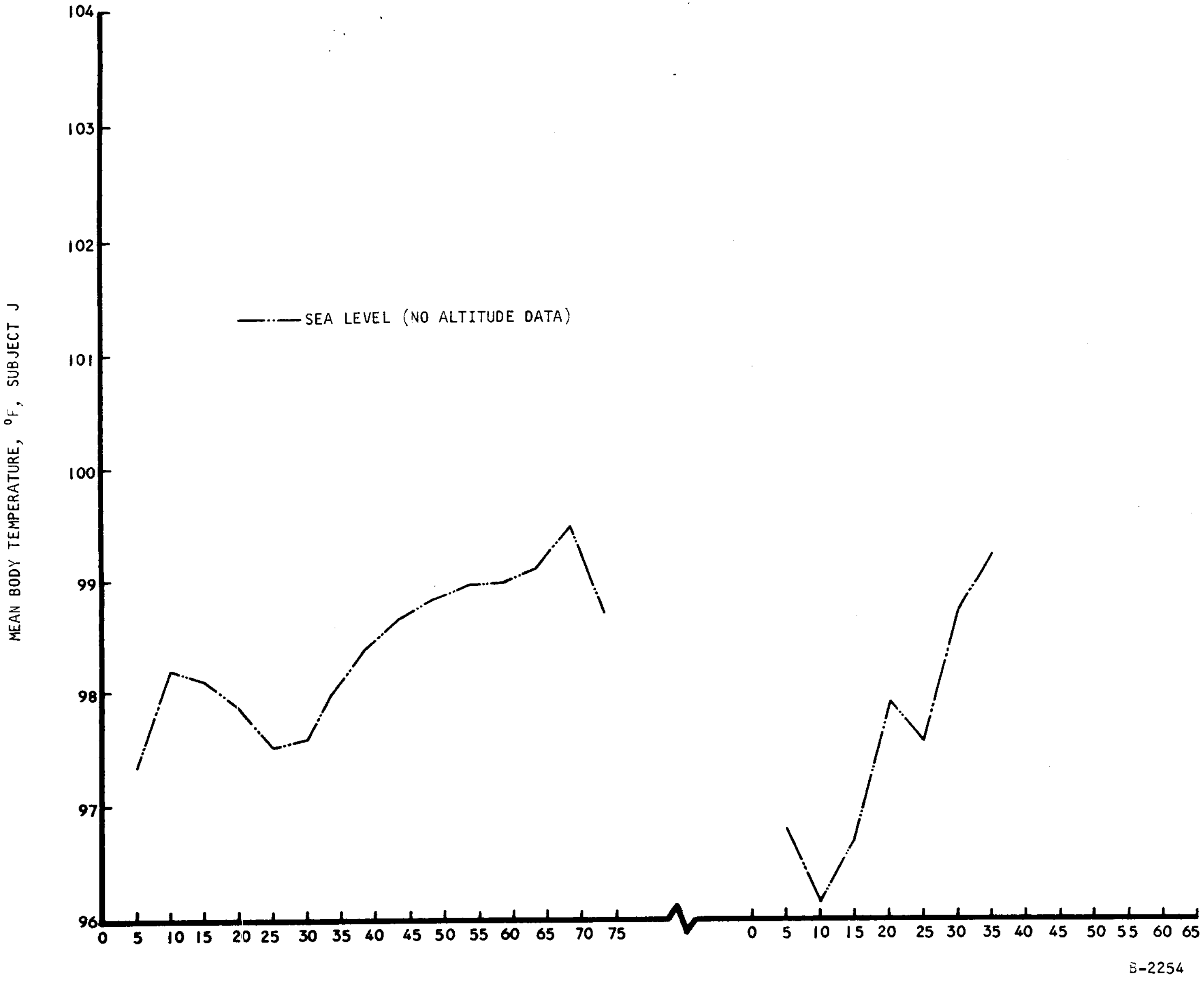


Figure 101. Mean Body Temperature, Subject J

HEART RATE

The following graphs (Figures 102 through 111) show the heart rate data that were recorded continuously during each test mode. Heart rates for the low and high activity levels are at the left and right, respectively, of each graph.

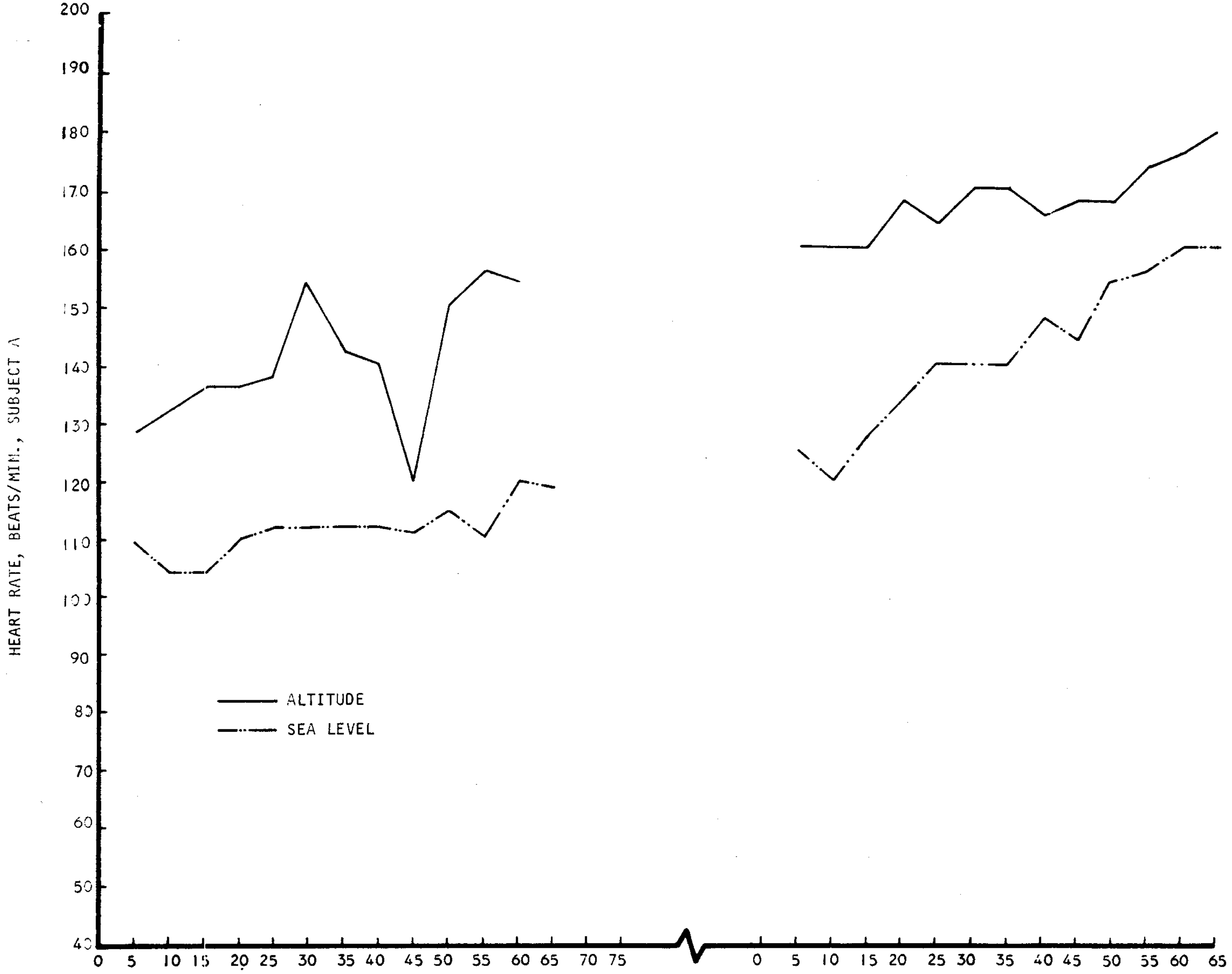


Figure 102. Heart Rate, Subject A

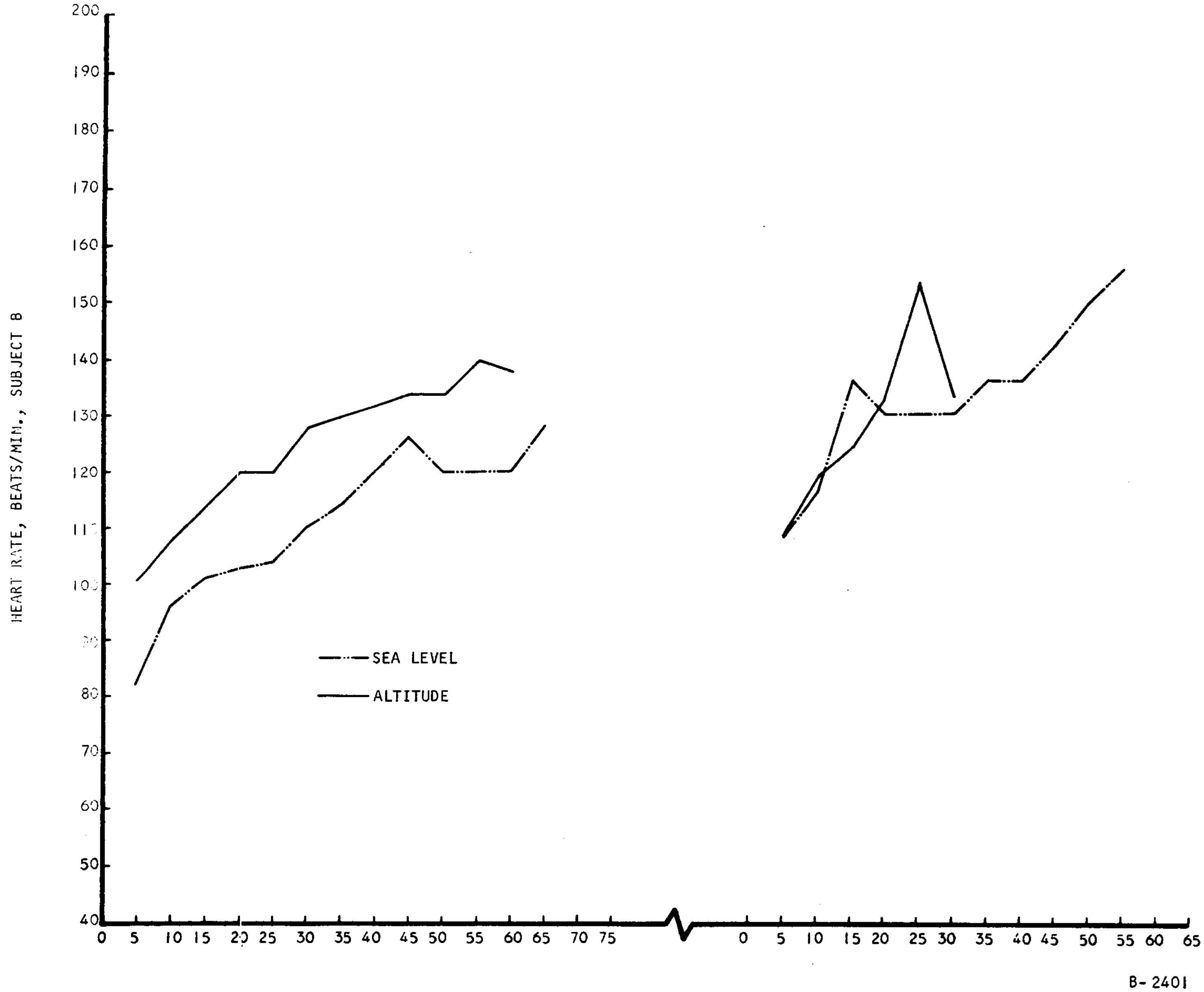


Figure 103. Heart Rate, Subject B

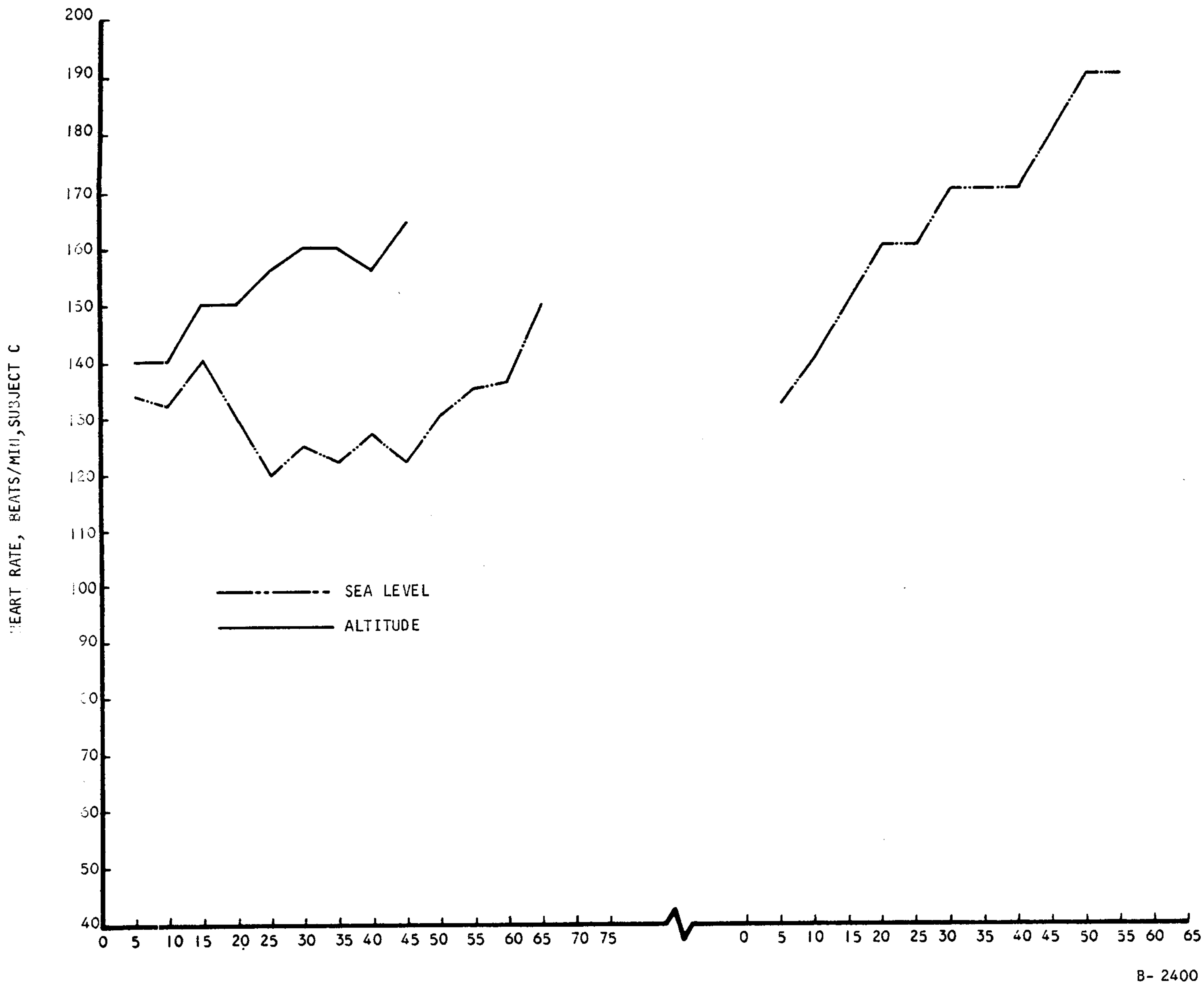


Figure 104. Heart Rate, Subject C

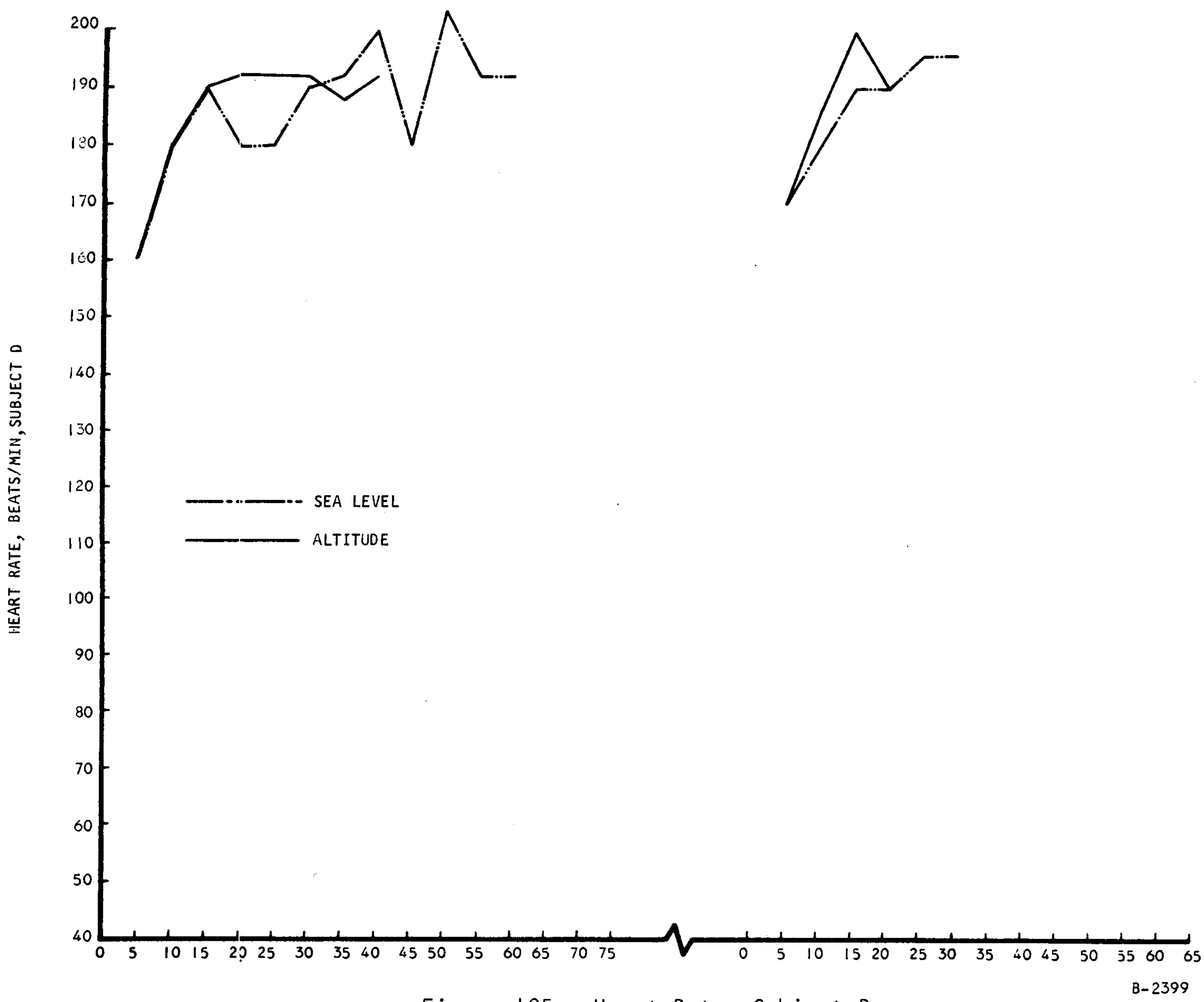


Figure 105. Heart Rate, Subject D

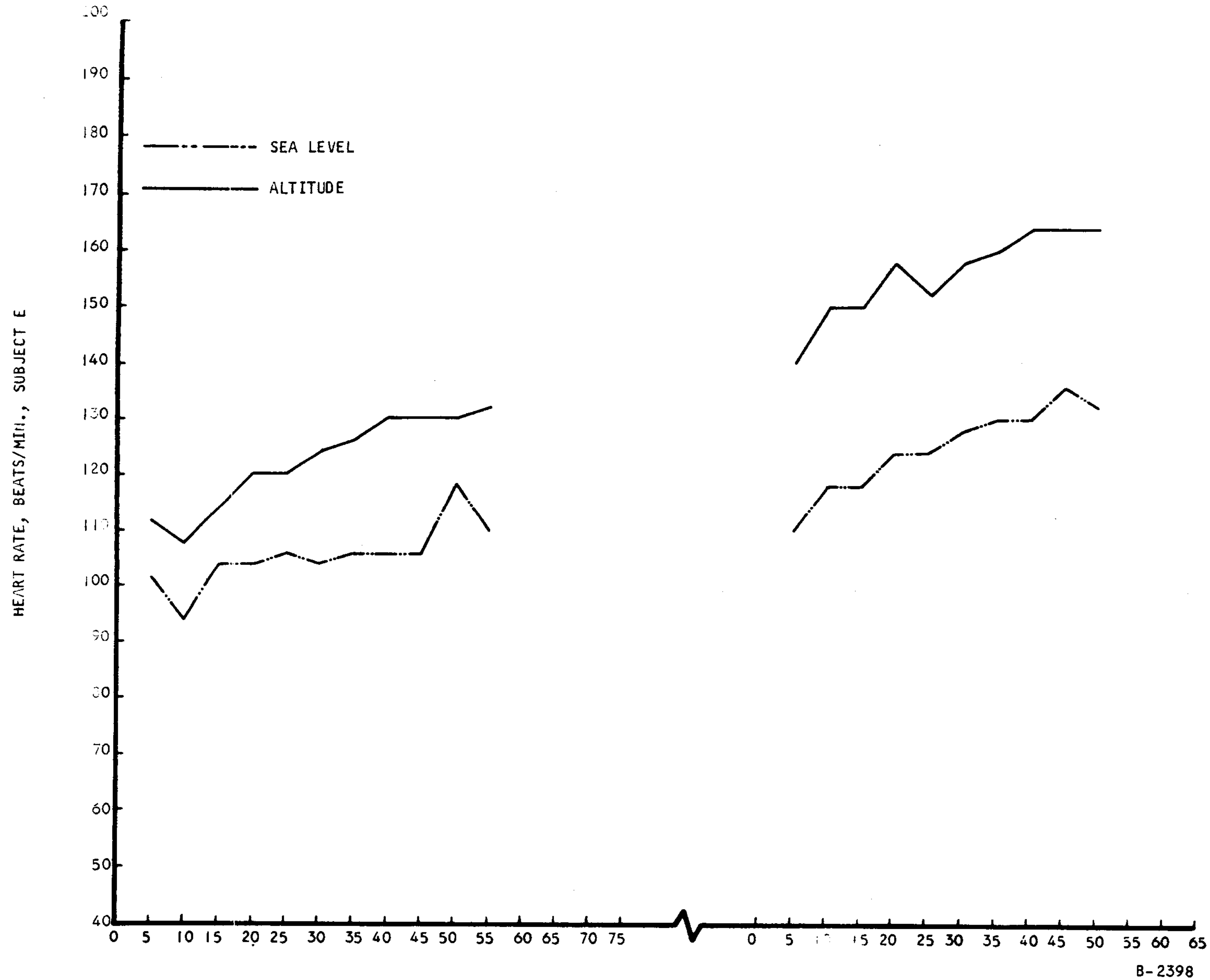


Figure 106. Heart Rate, Subject E

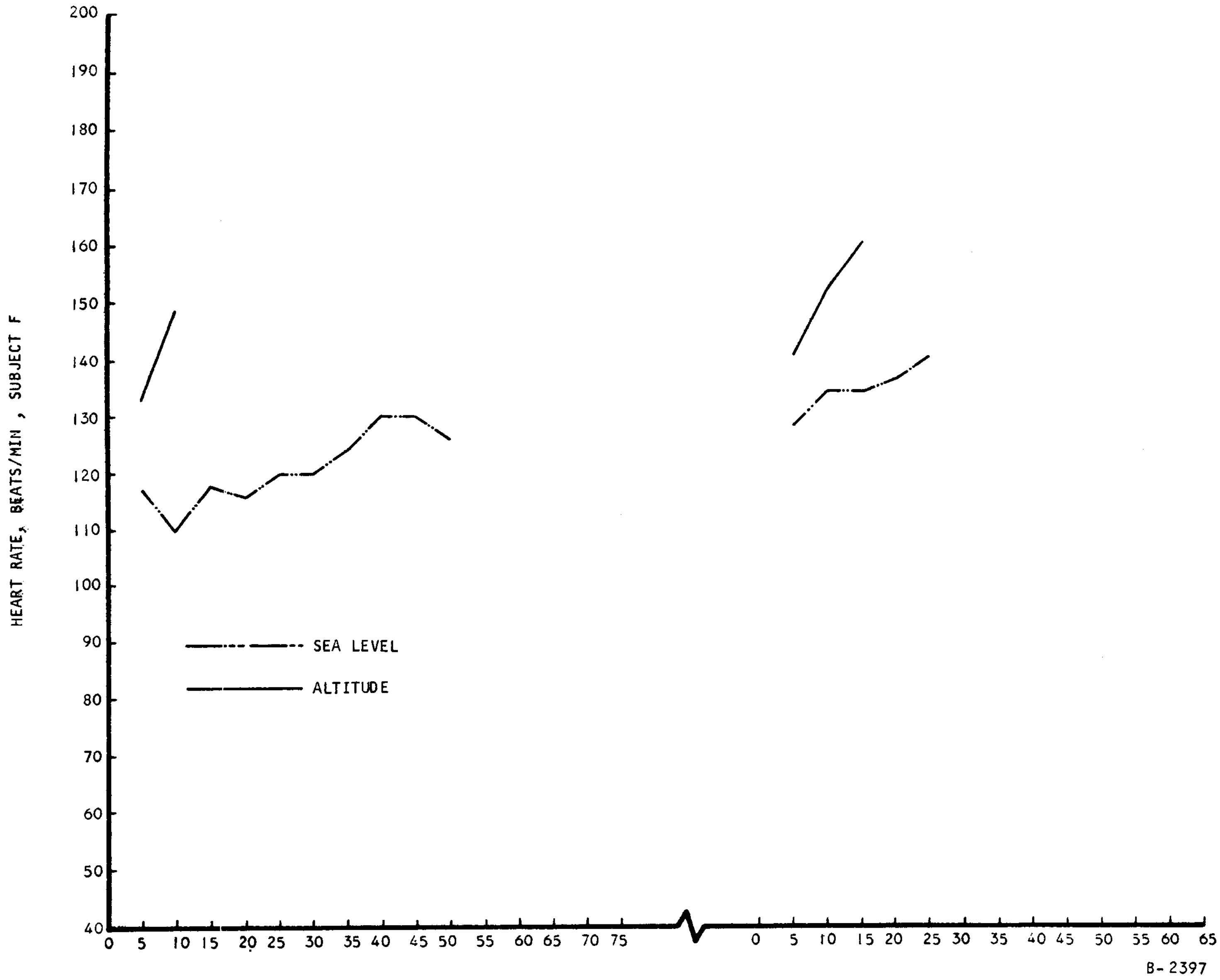


Figure 107. Heart Rate, Subject F

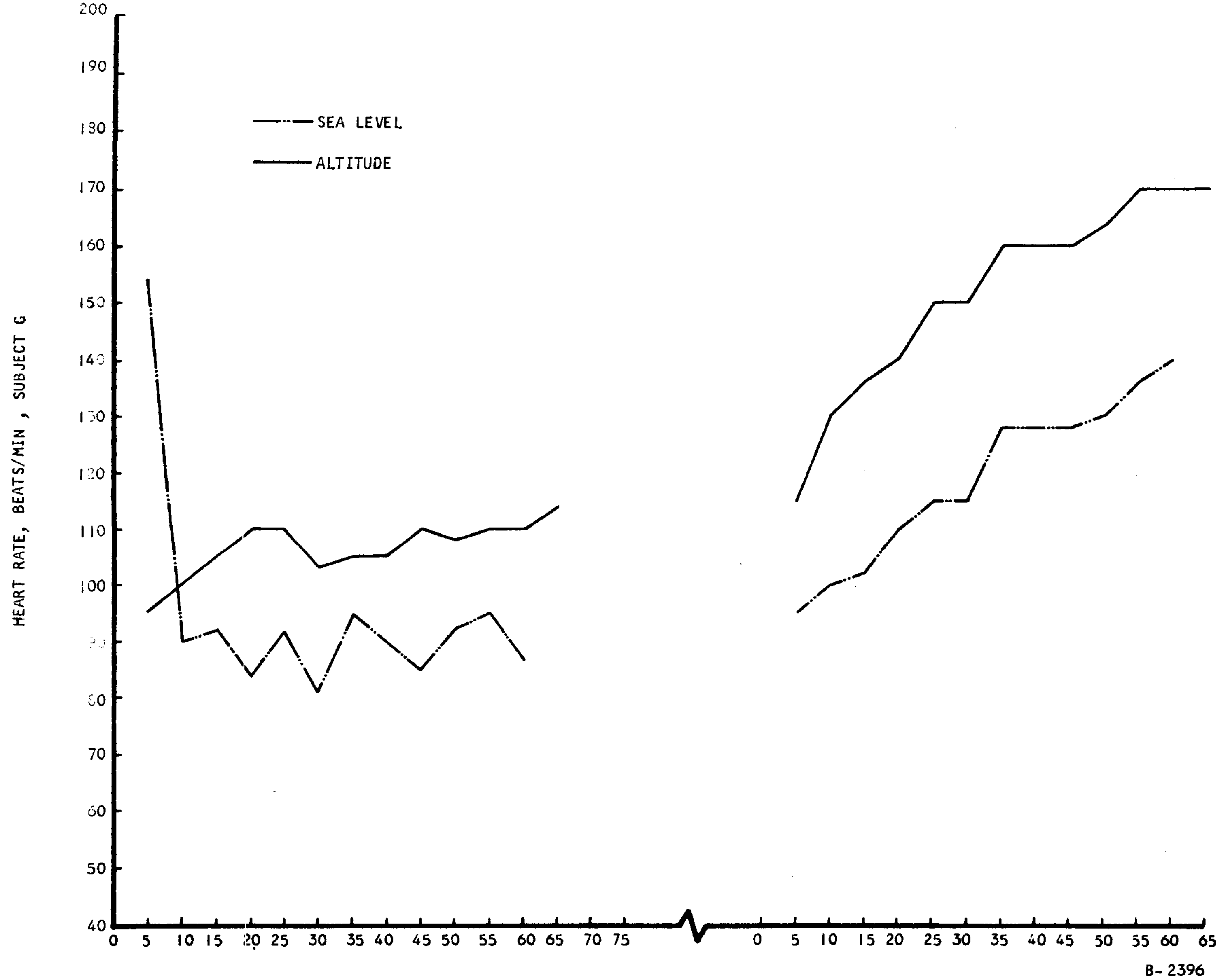
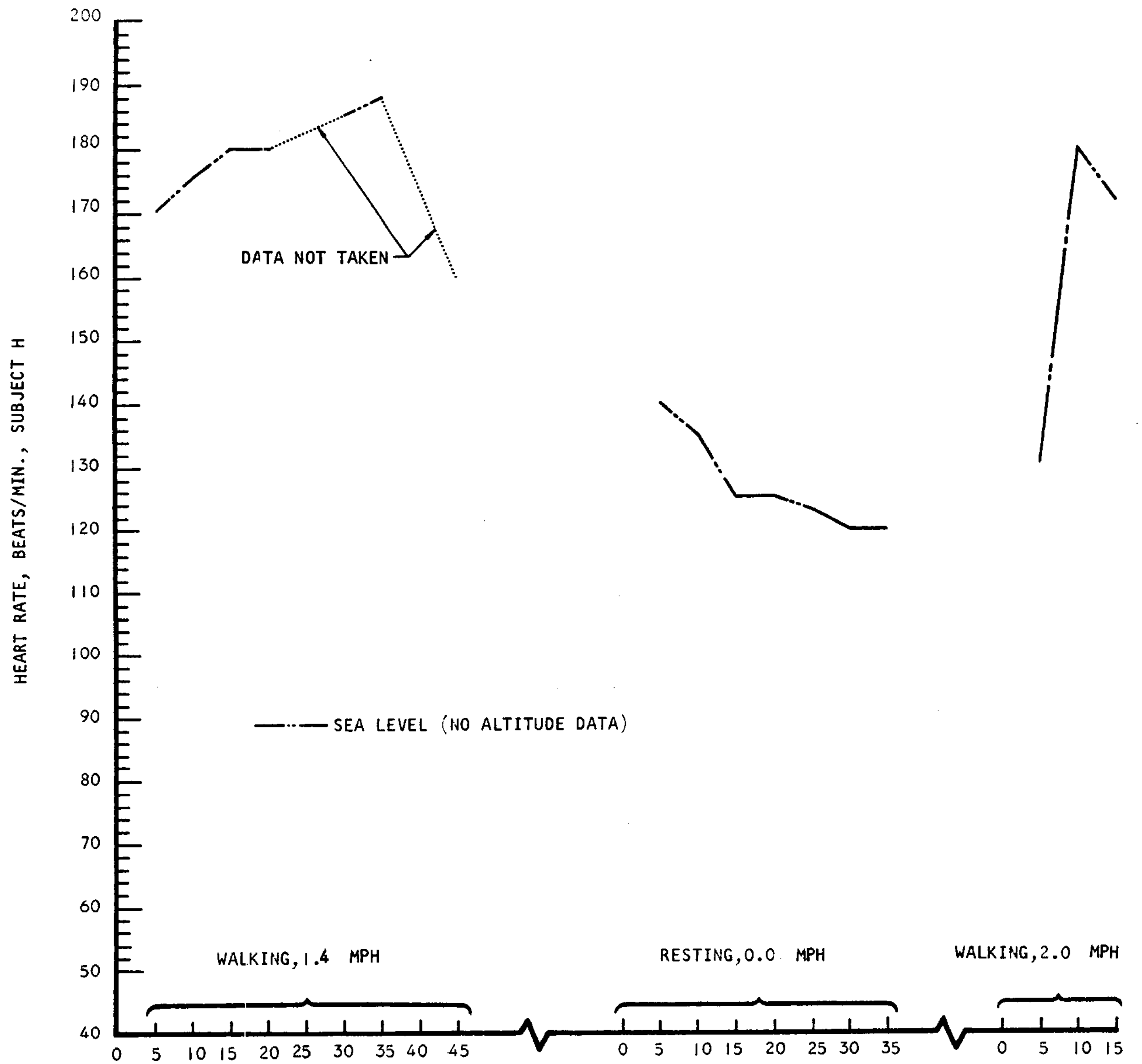


Figure 108. Heart Rate, Subject G



B-2378

Figure 109. Heart Rate, Subject H

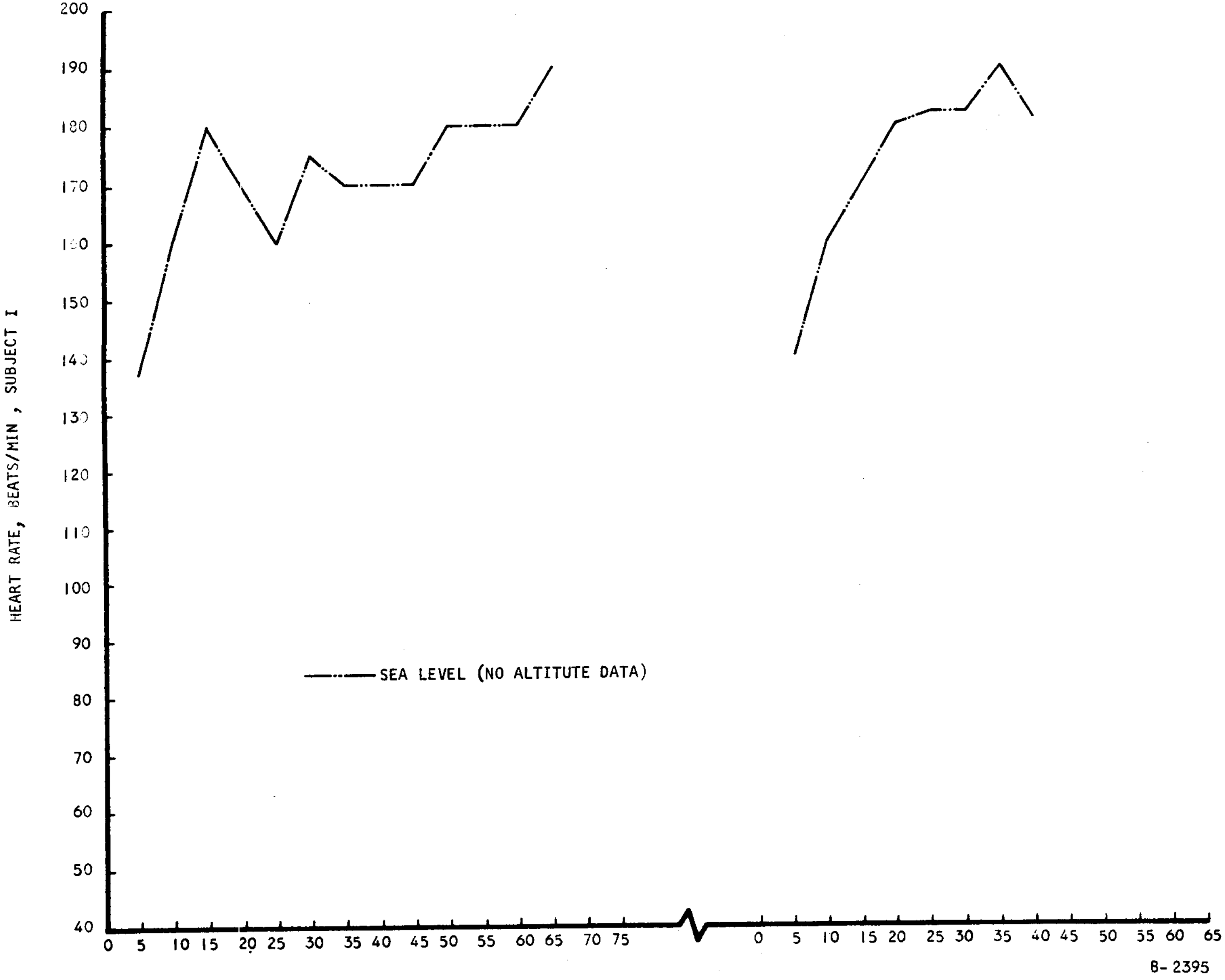


Figure 110. Heart Rate, Subject I

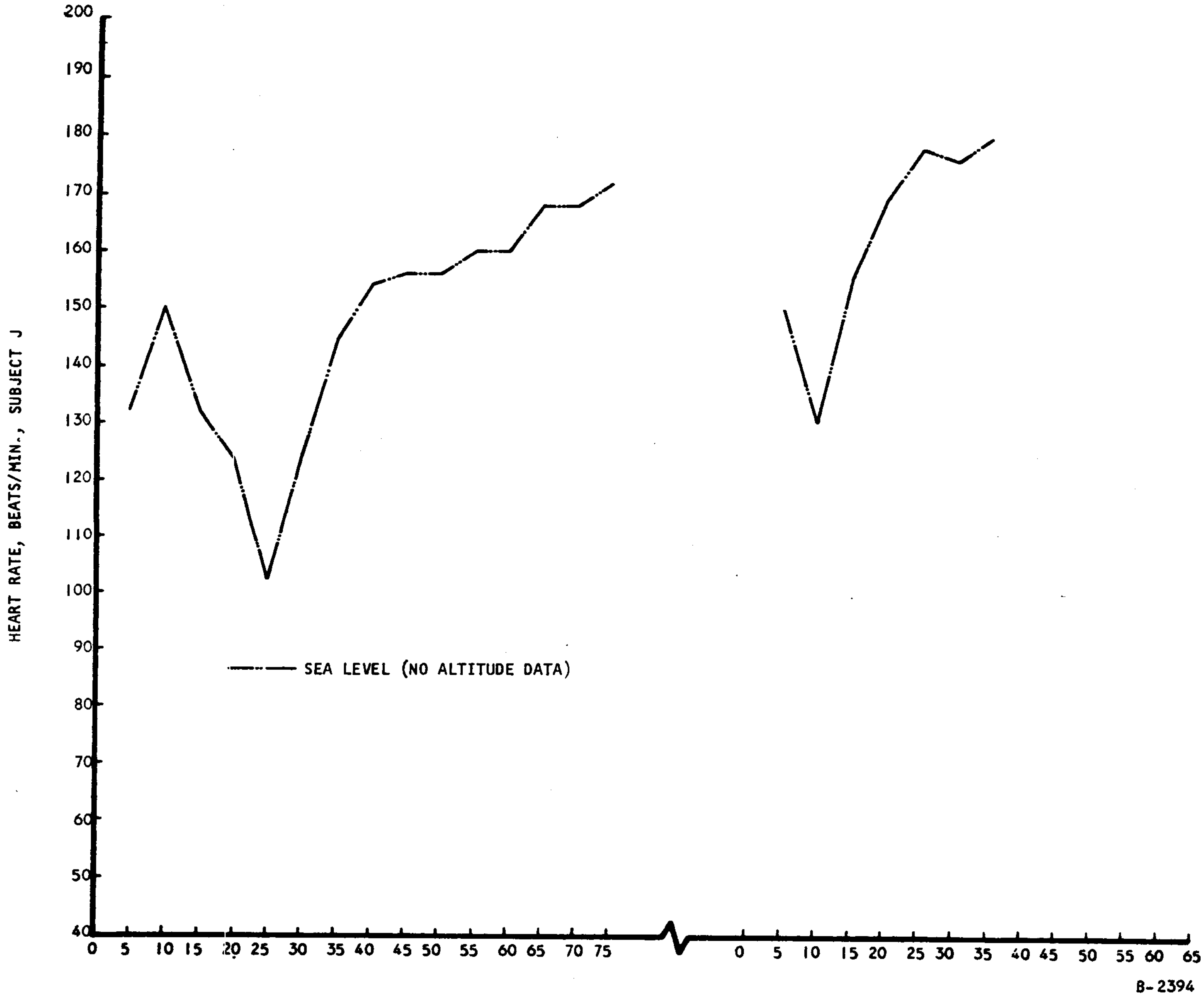


Figure III. Heart Rate, Subject J

MINUTE VOLUME

The data obtained for minute volumes, at ambient temperature and pressure conditions, are presented in Figures 112 through 121. Minute volumes, especially when adjusted for metabolic rate as previously discussed, are lower at reduced pressure than at sea level. Minute volumes for 1.4 and 2.0 mph exercise level, respectively, are shown at left and at right on each figure.

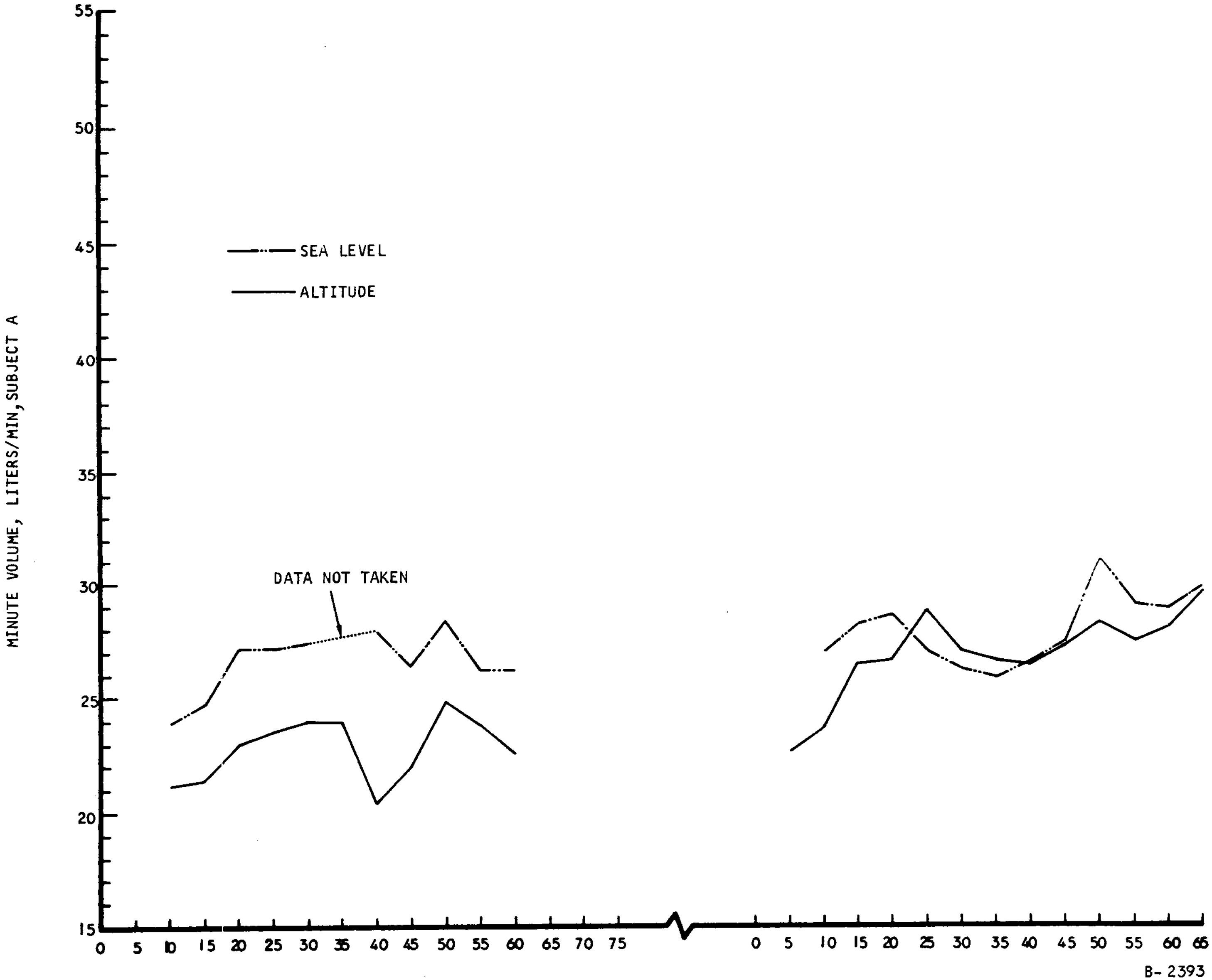


Figure 112. Minute Volume, Subject A

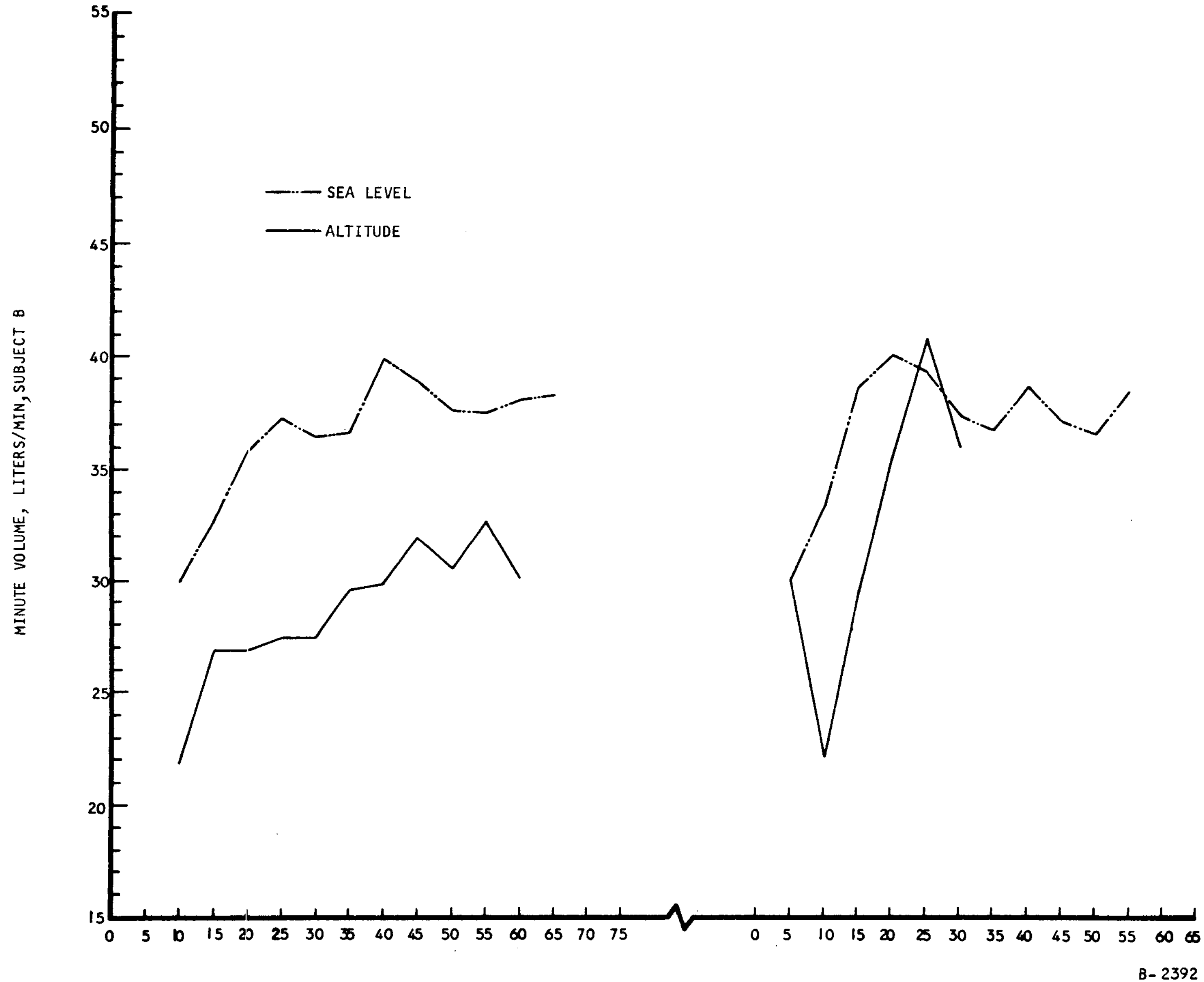


Figure 113. Minute Volume, Subject B

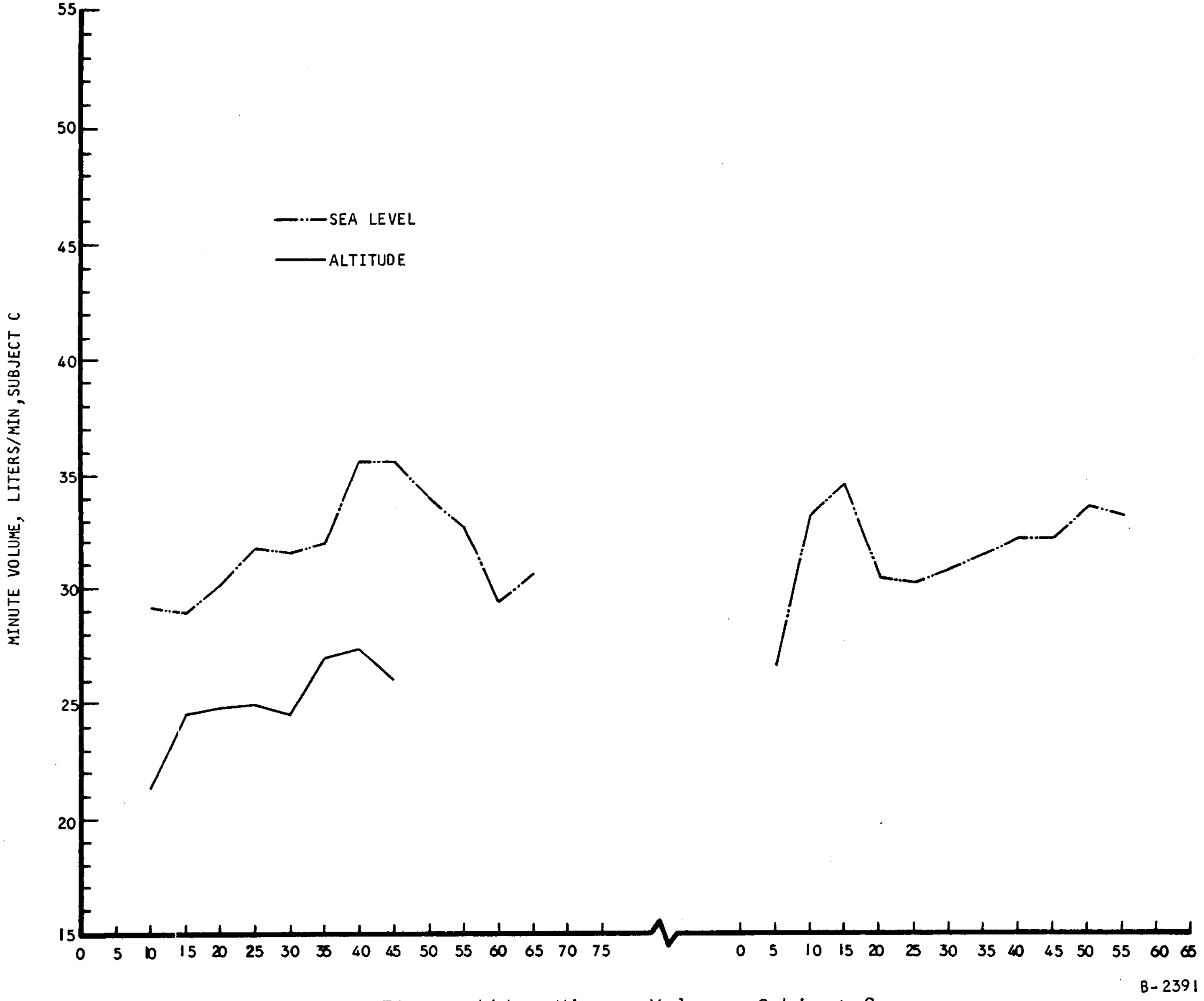


Figure 114. Minute Volume, Subject C

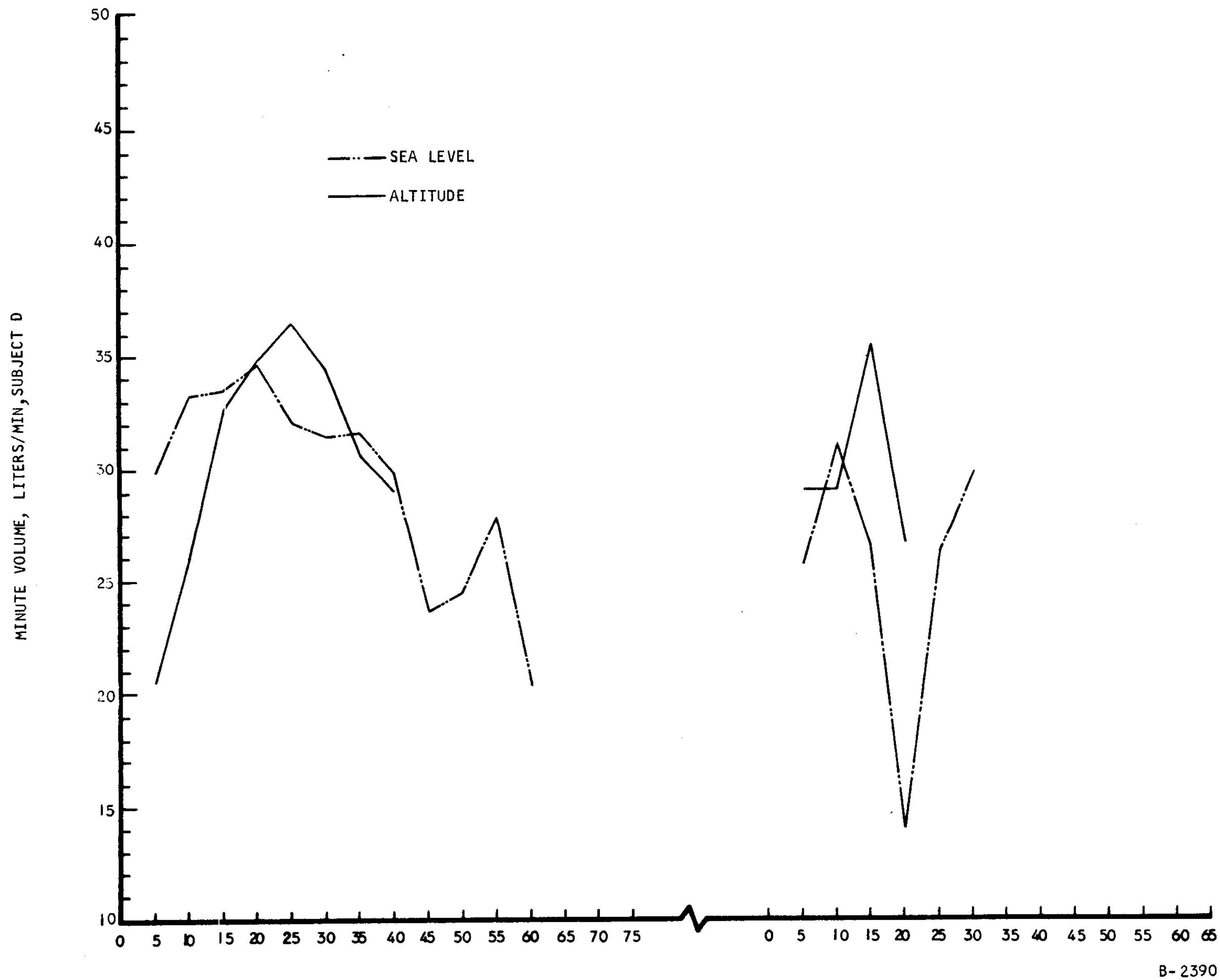


Figure 115. Minute Volume, Subject D

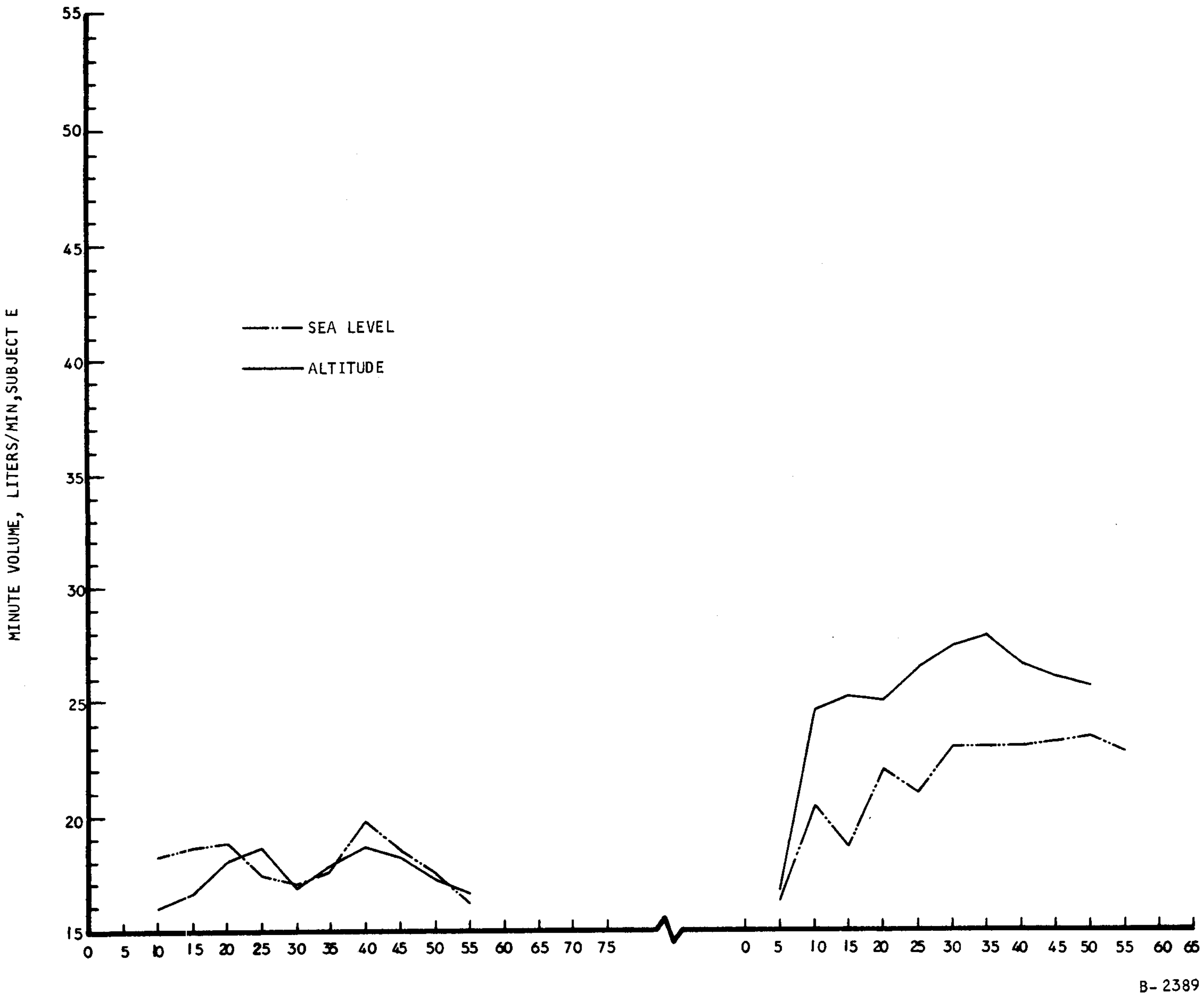
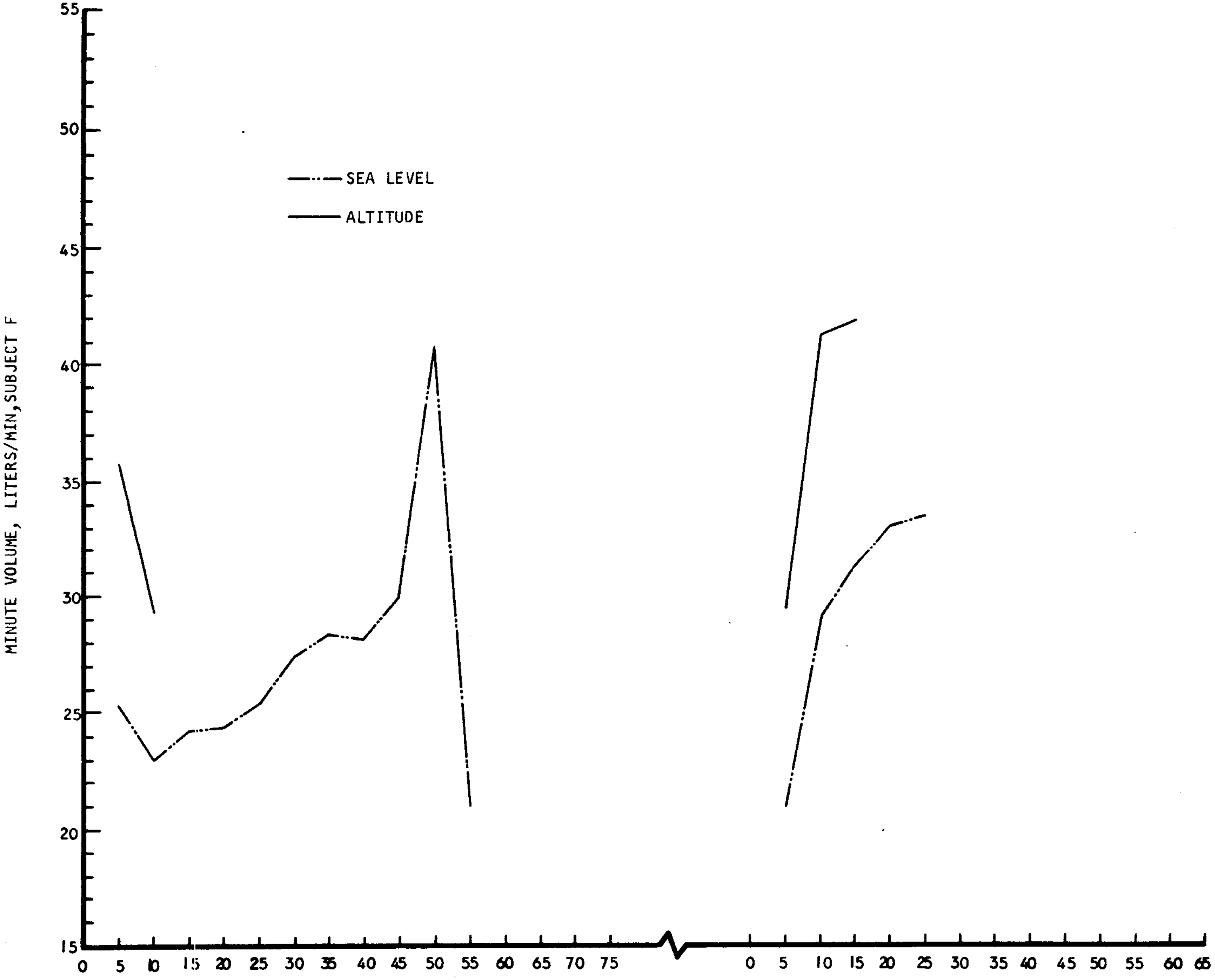


Figure 116. Minute Volume, Subject E



B-2388

Figure 117. Minute Volume, Subject F

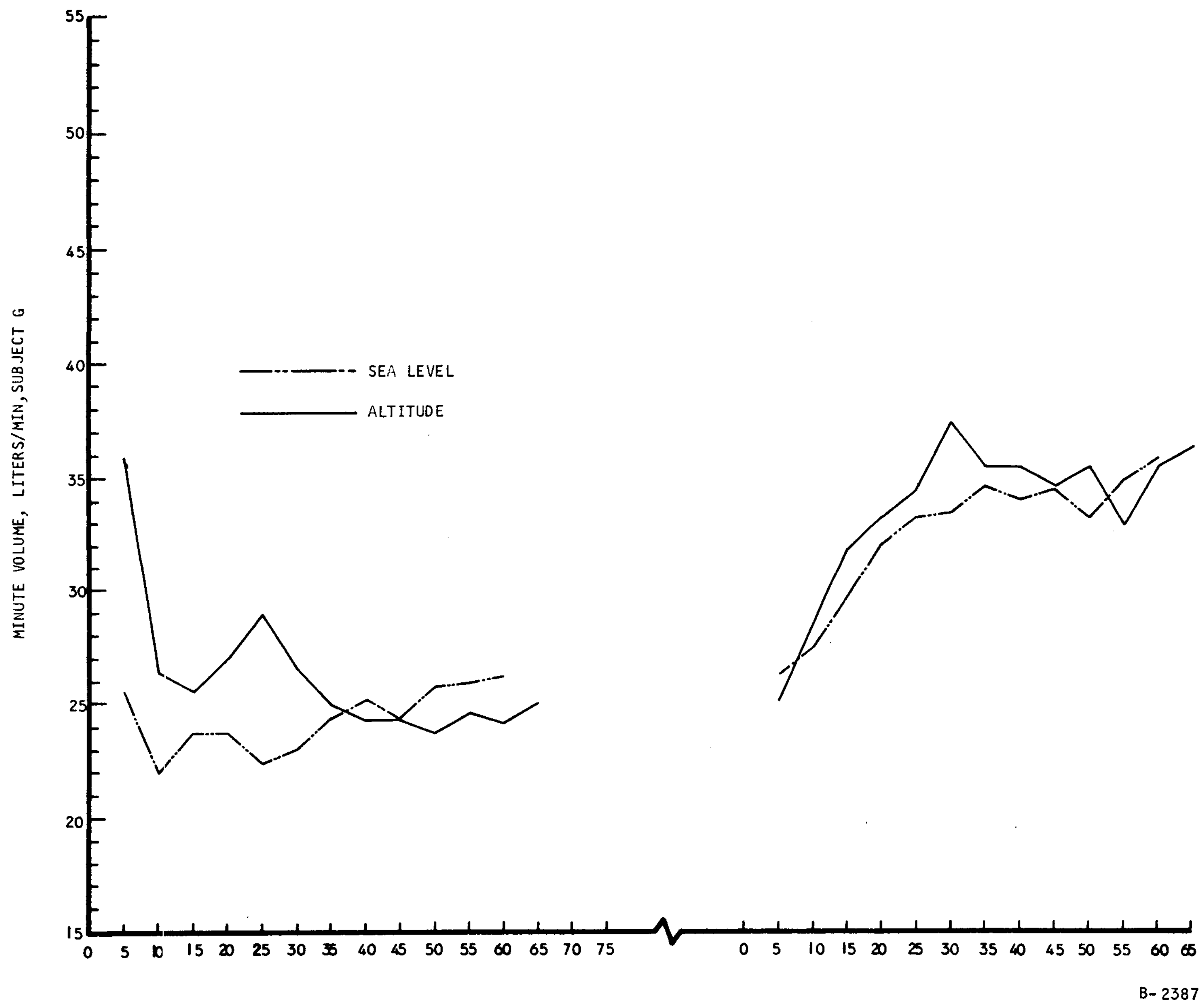


Figure 118. Minute Volume, Subject G

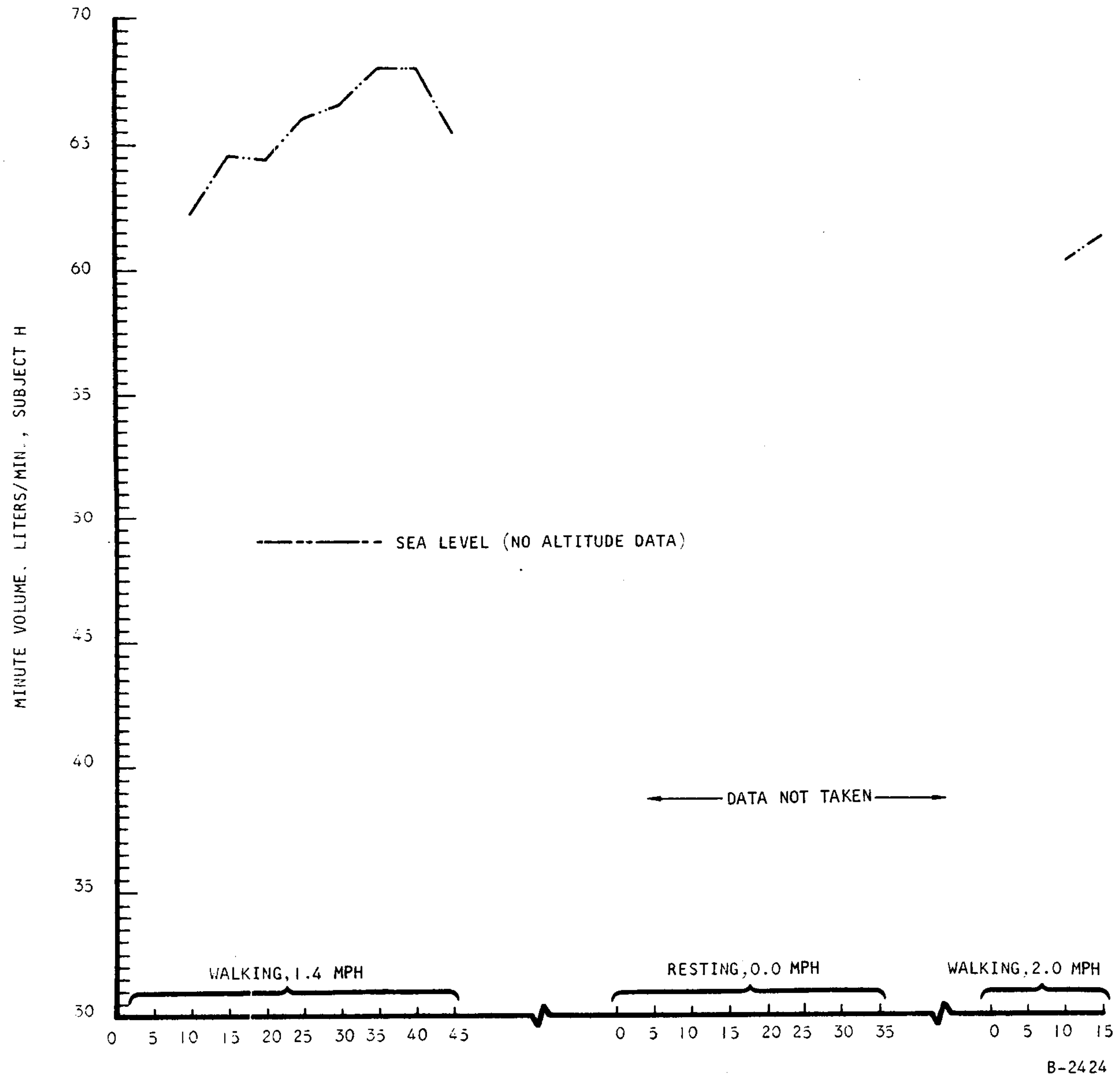


Figure 119. Minute Volume, Subject H

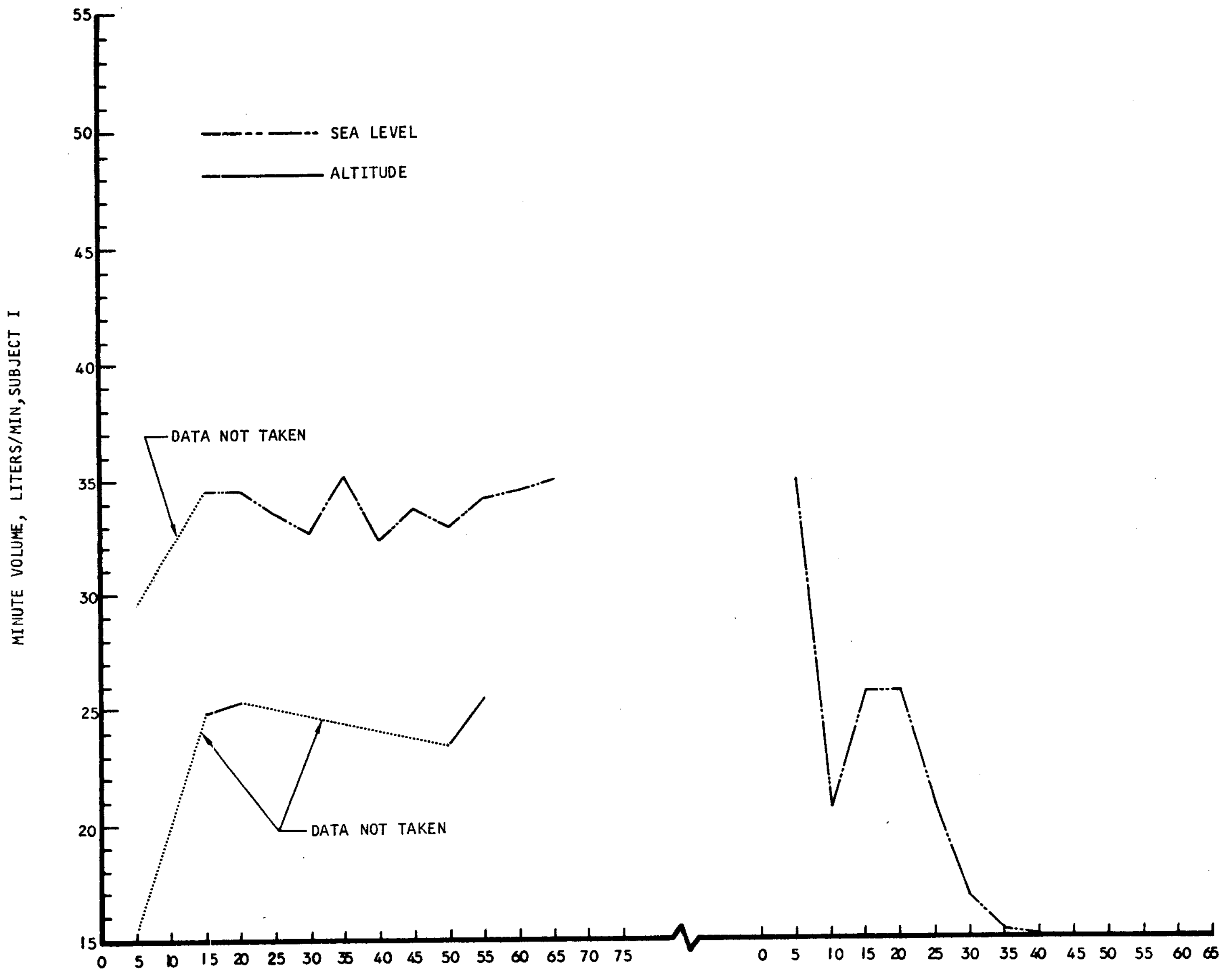


Figure 120. Minute Volume, Subject I

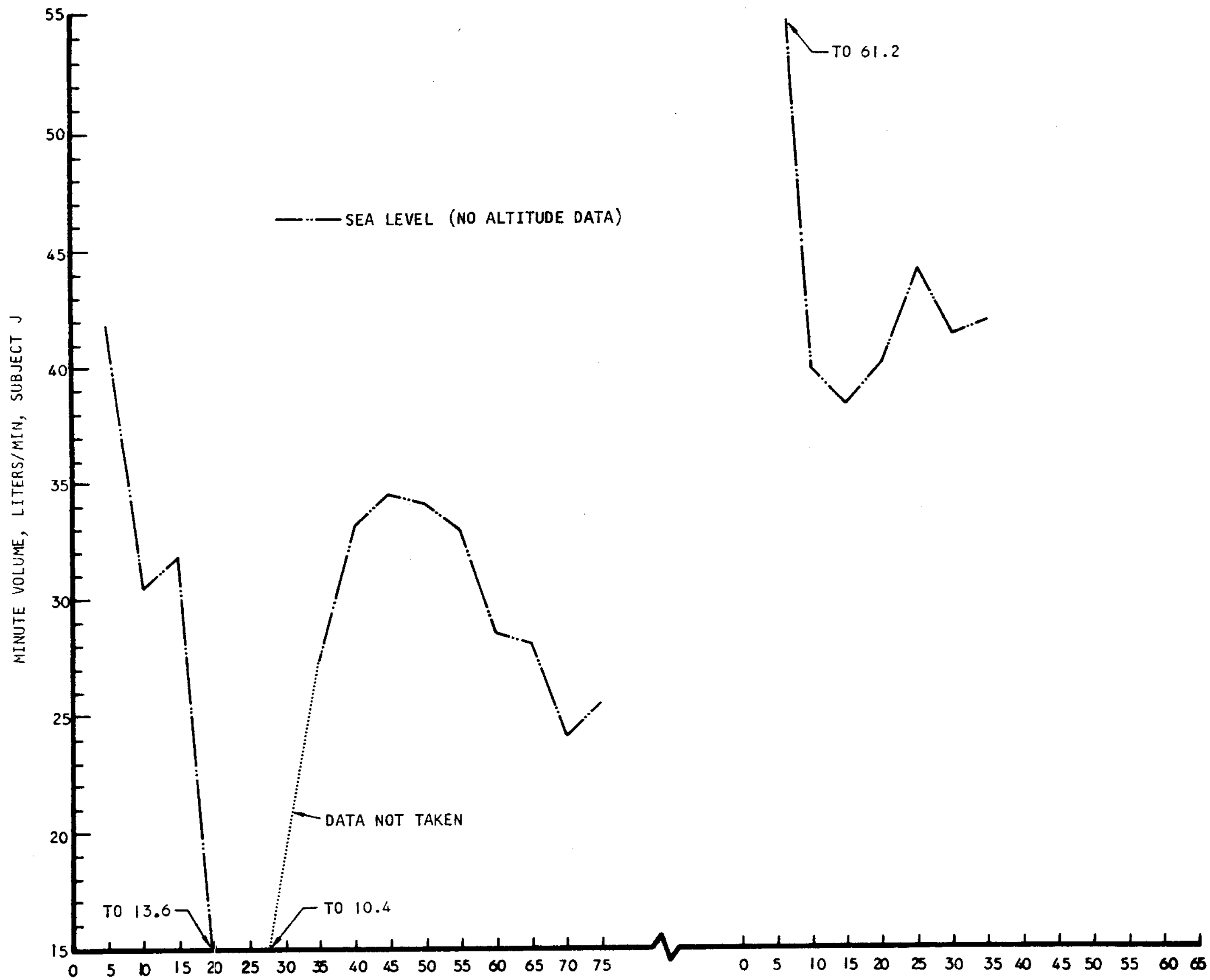


Figure 121. Minute Volume, Subject J

B-2425

RESPIRATORY HEAT LOSS

The data obtained showed that heat loss from the body during the process of respiration is less at altitude than at sea level. Respiratory heat loss ranged from -7 to 110 Btu/hr. Figures 122 through 131 follow the convention of this report, with the data for low and high activity levels arranged on the left and right, respectively, of each graph.

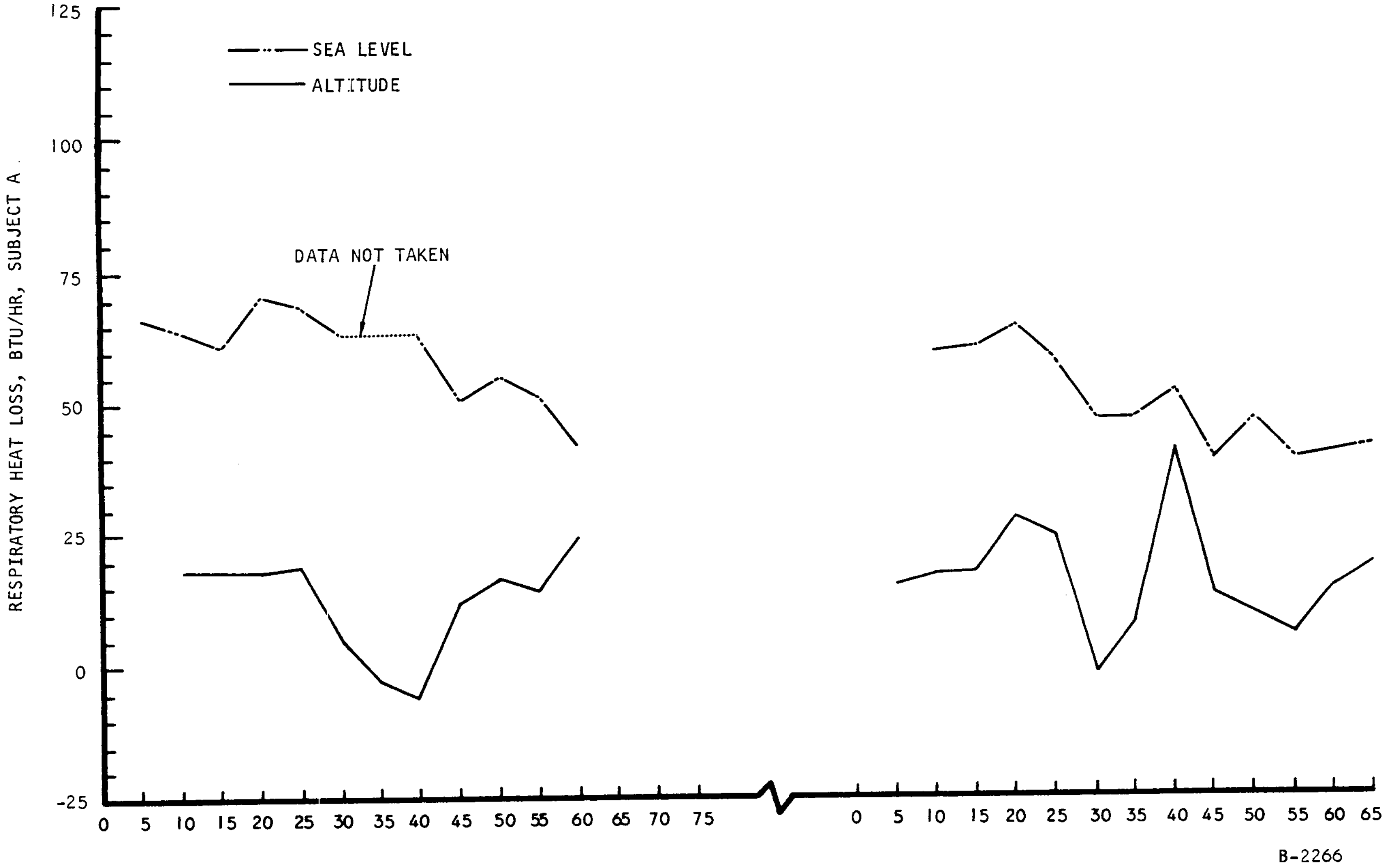
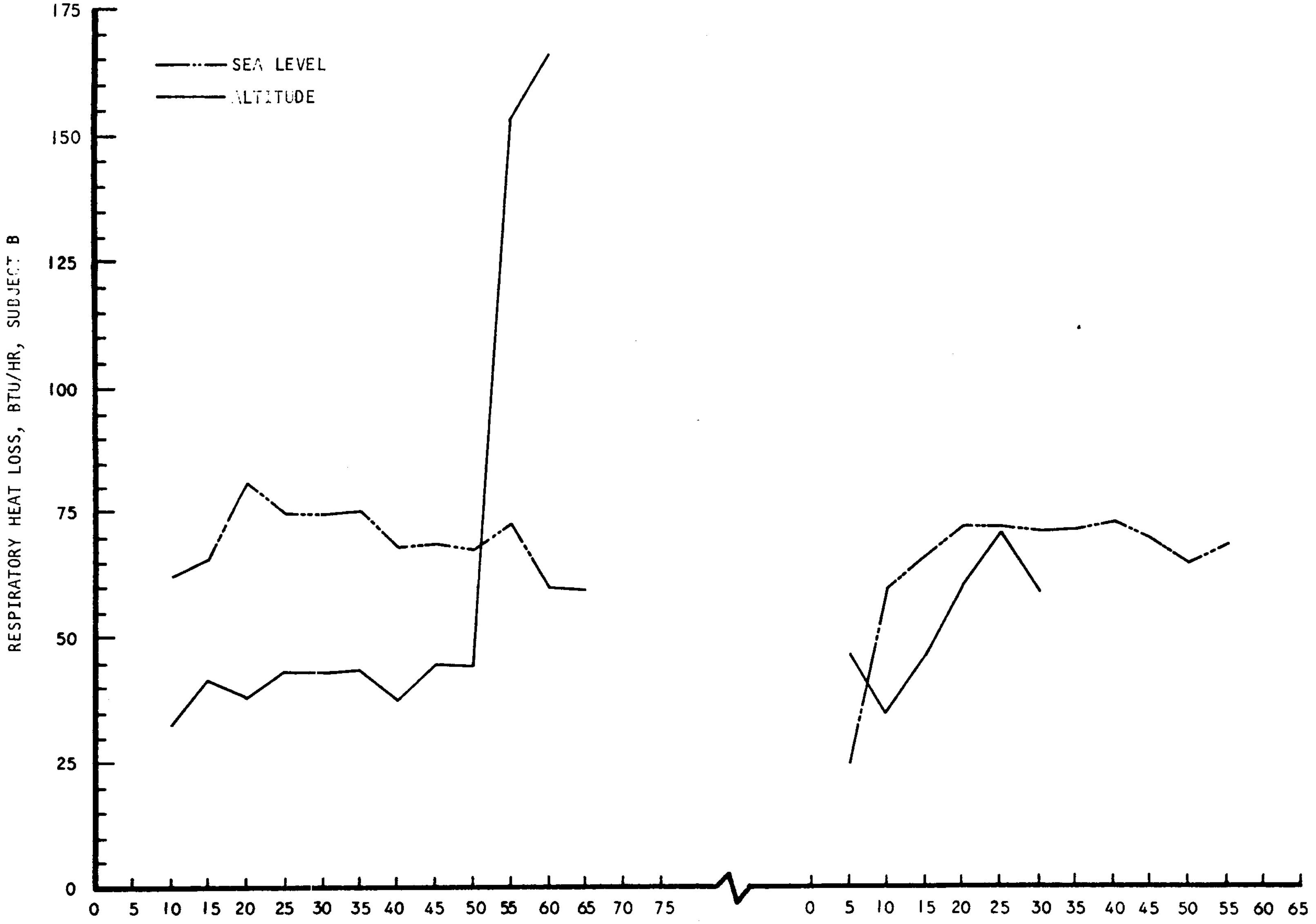


Figure 122. Respiratory Heat Loss, Subject A



B-2265

Figure 123. Respiratory Heat Loss, Subject B

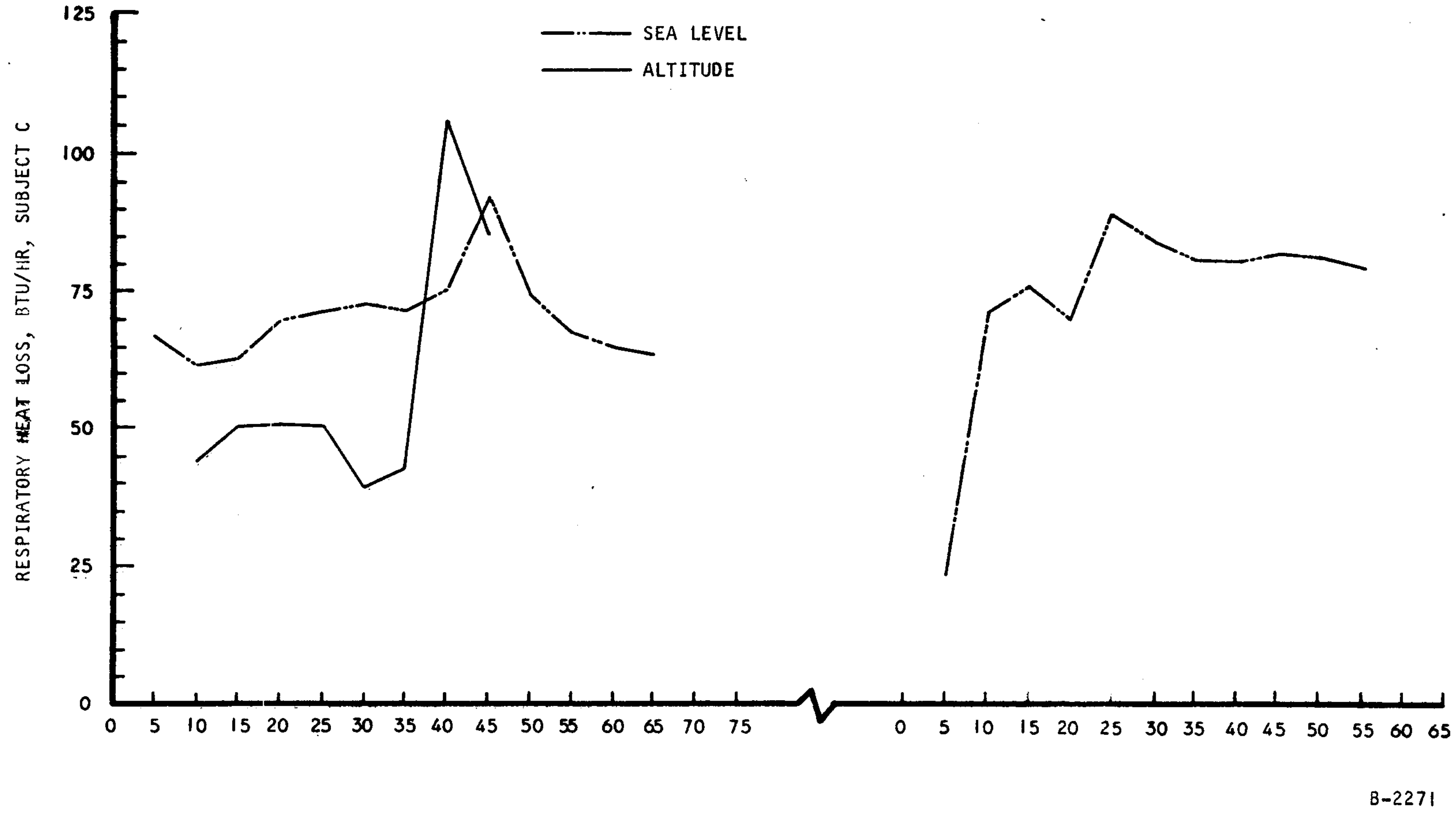


Figure 124. Respiratory Heat Loss, Subject C

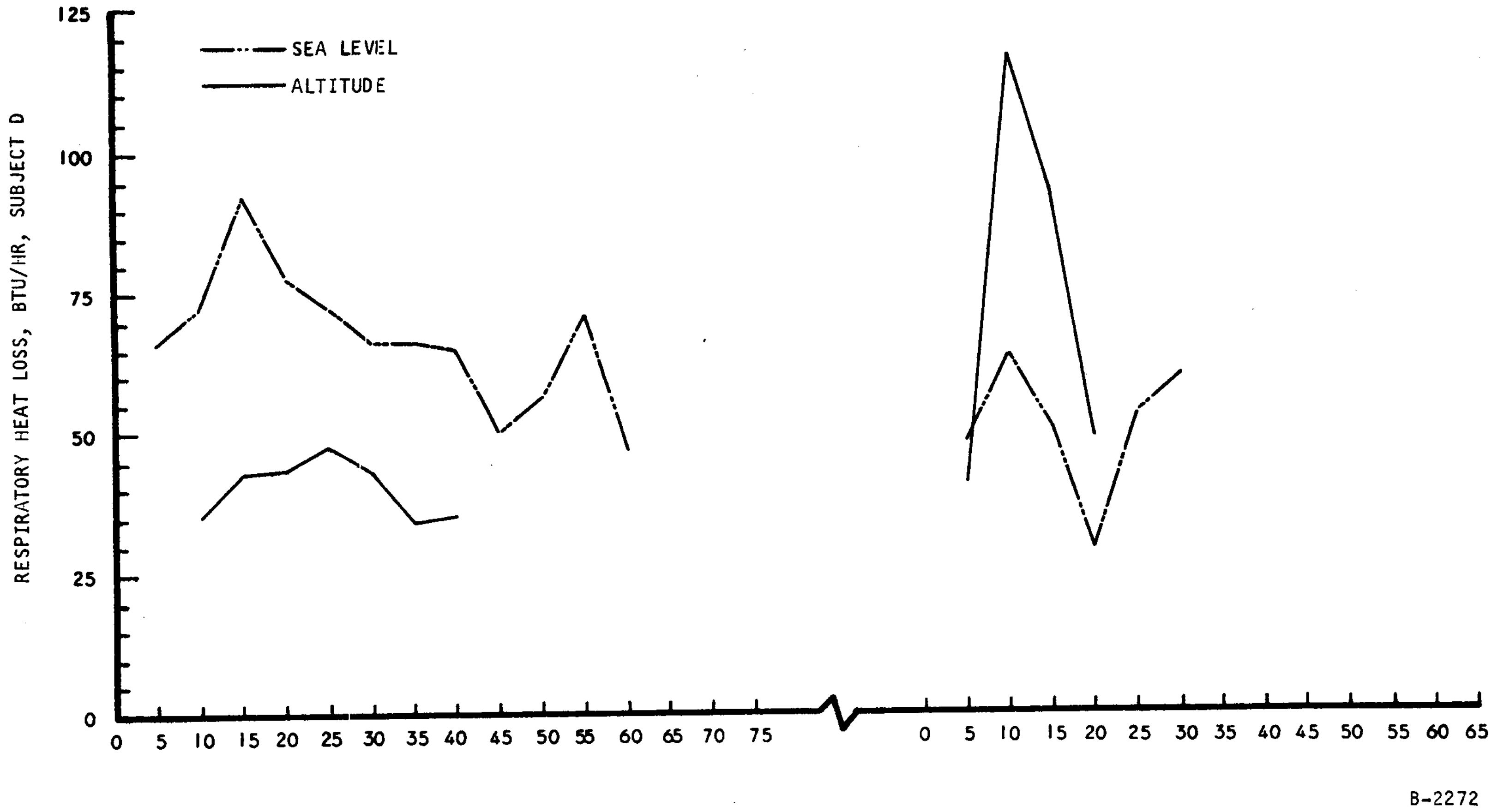


Figure 125. Respiratory Heat Loss, Subject D

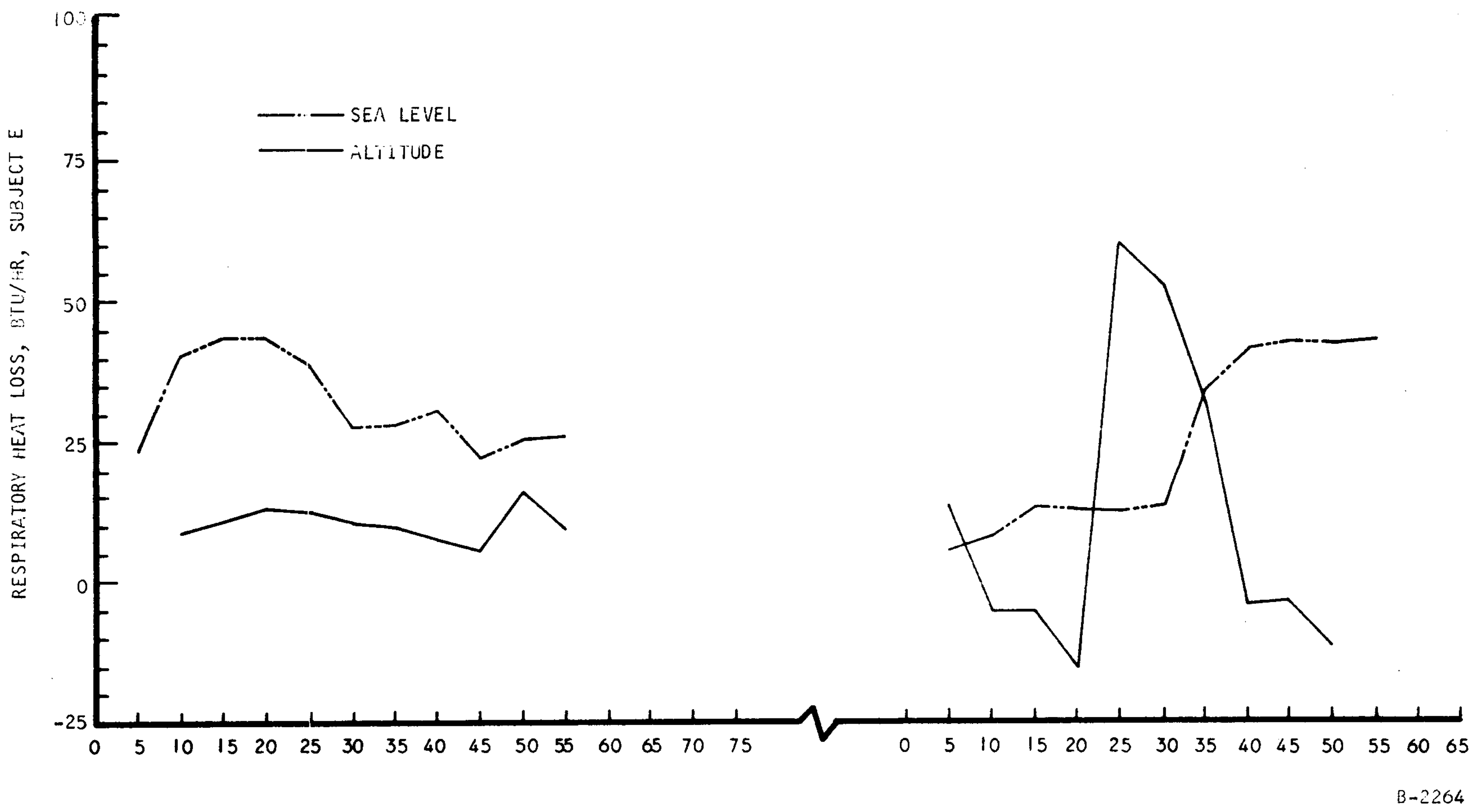


Figure 126. Respiratory Heat Loss, Subject E

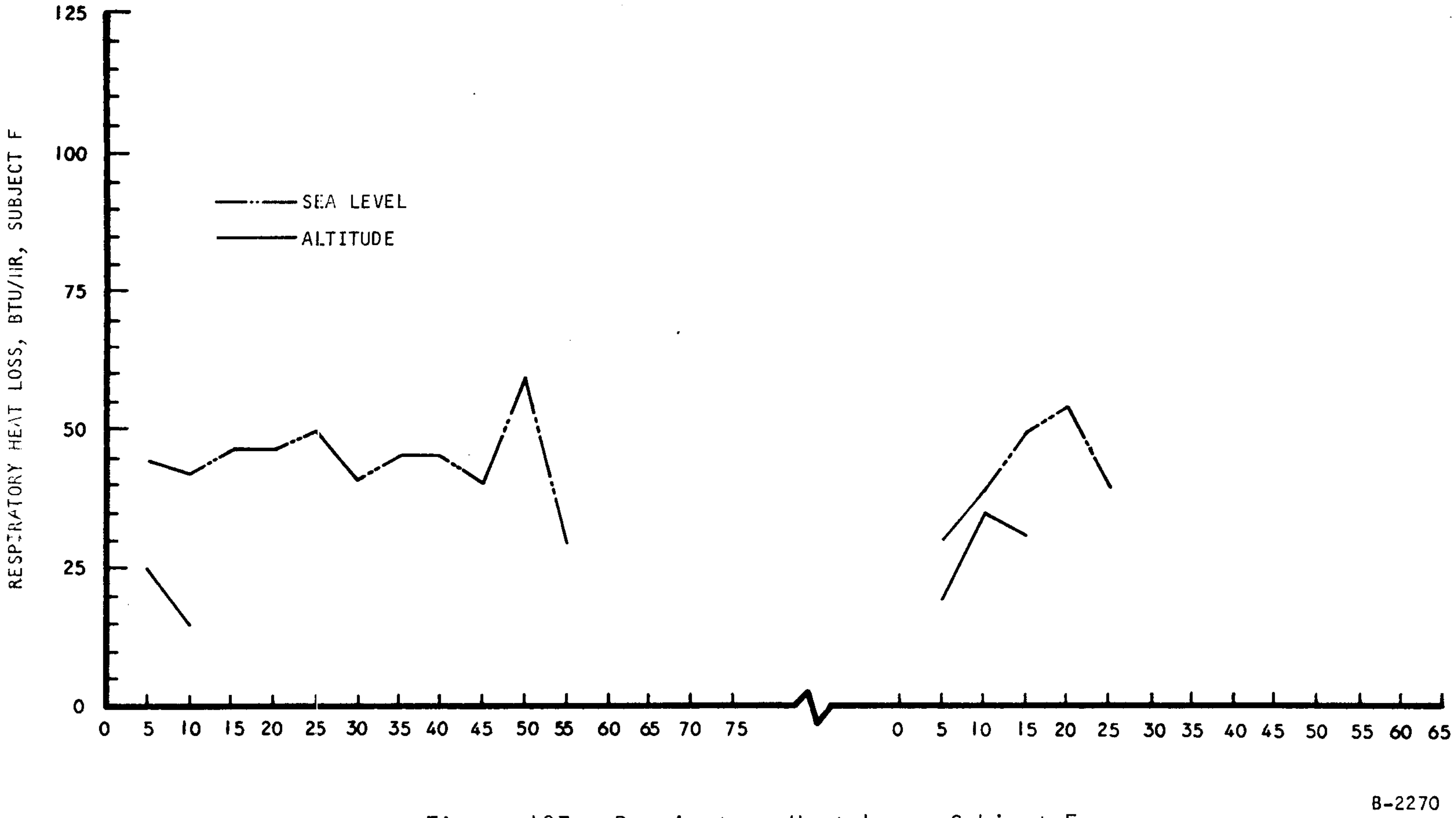


Figure 127. Respiratory Heat Loss, Subject F

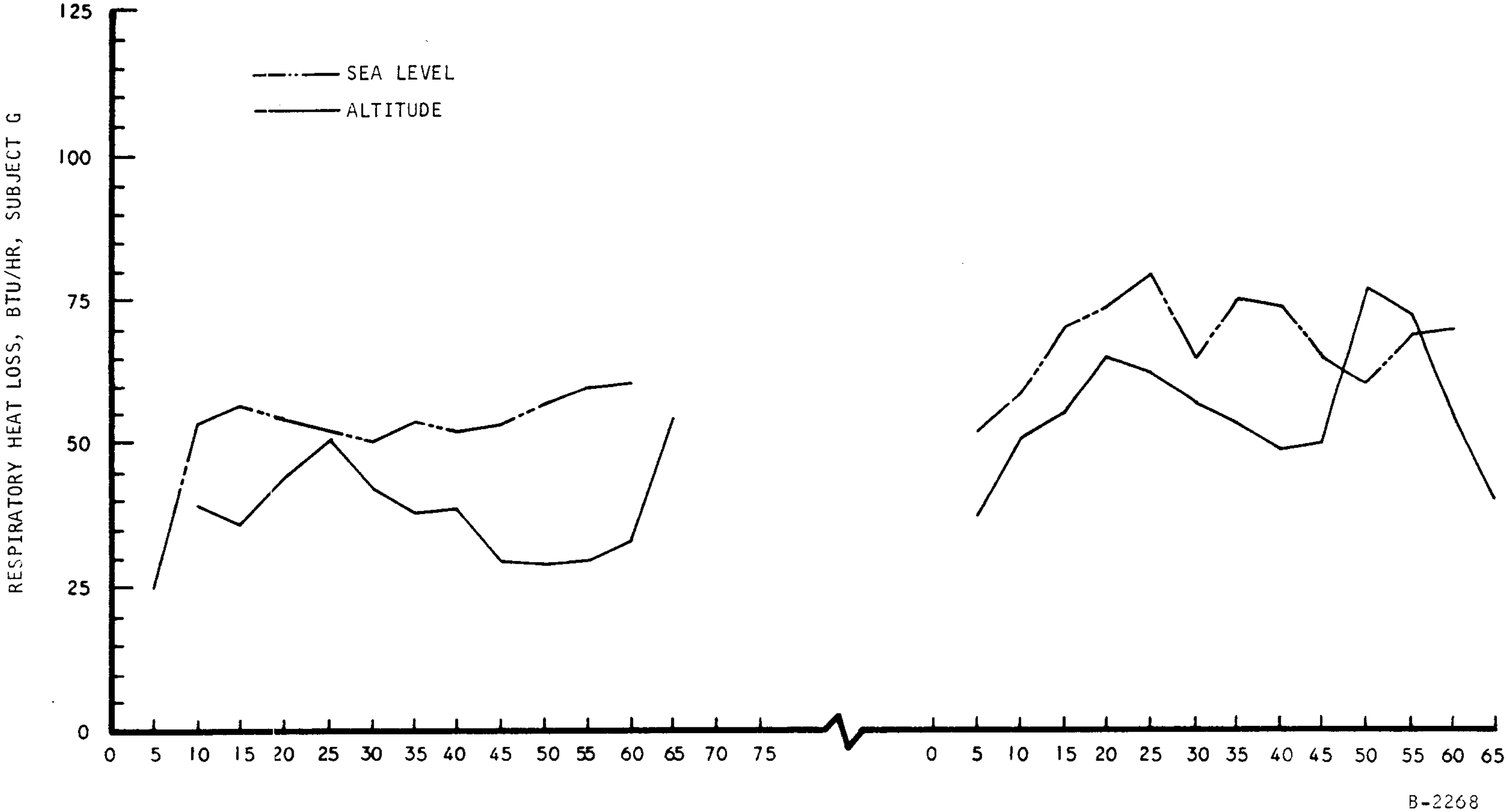


Figure 128. Respiratory Heat Loss, Subject G

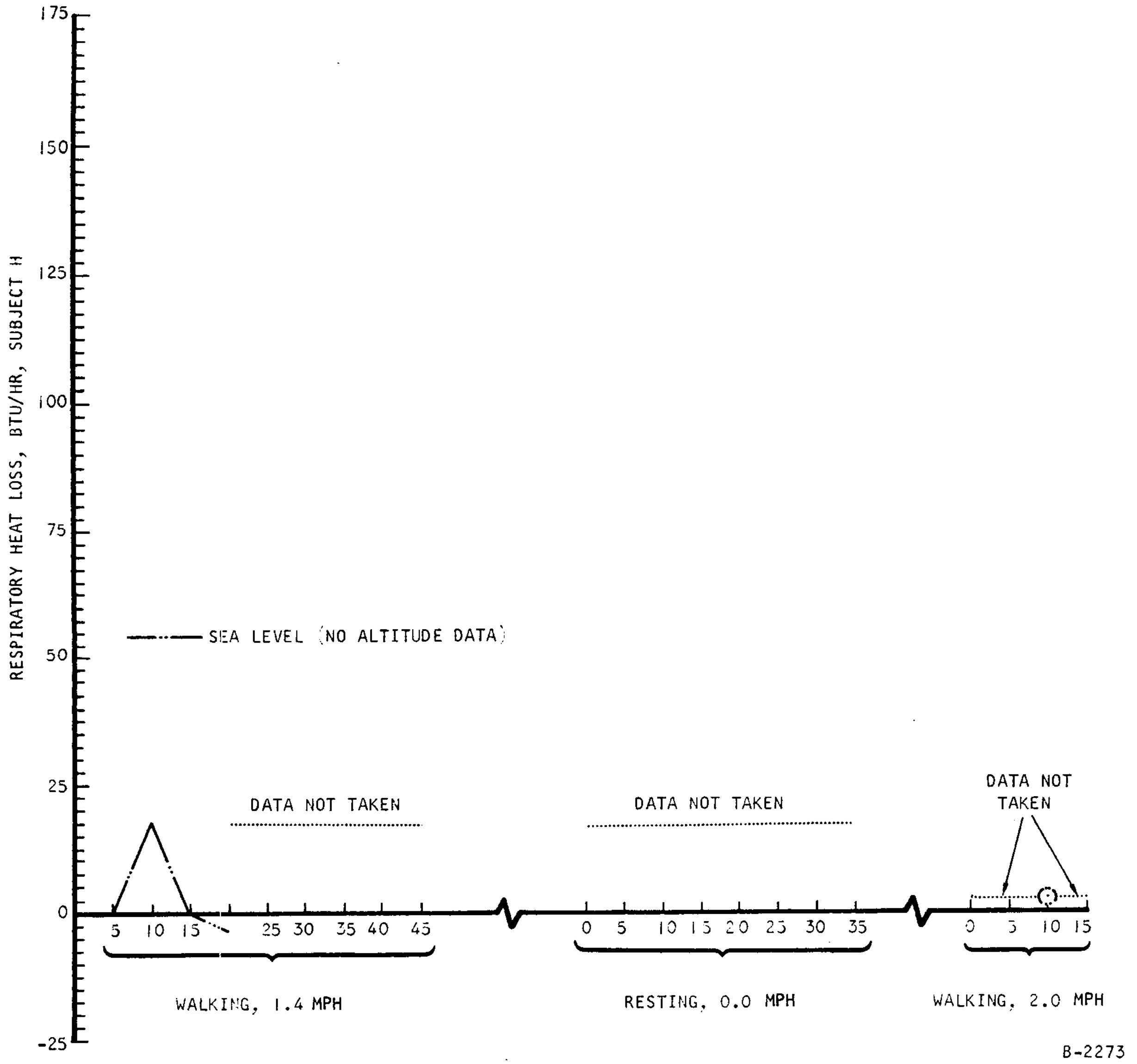


Figure 129. Respiratory Heat Loss, Subject H

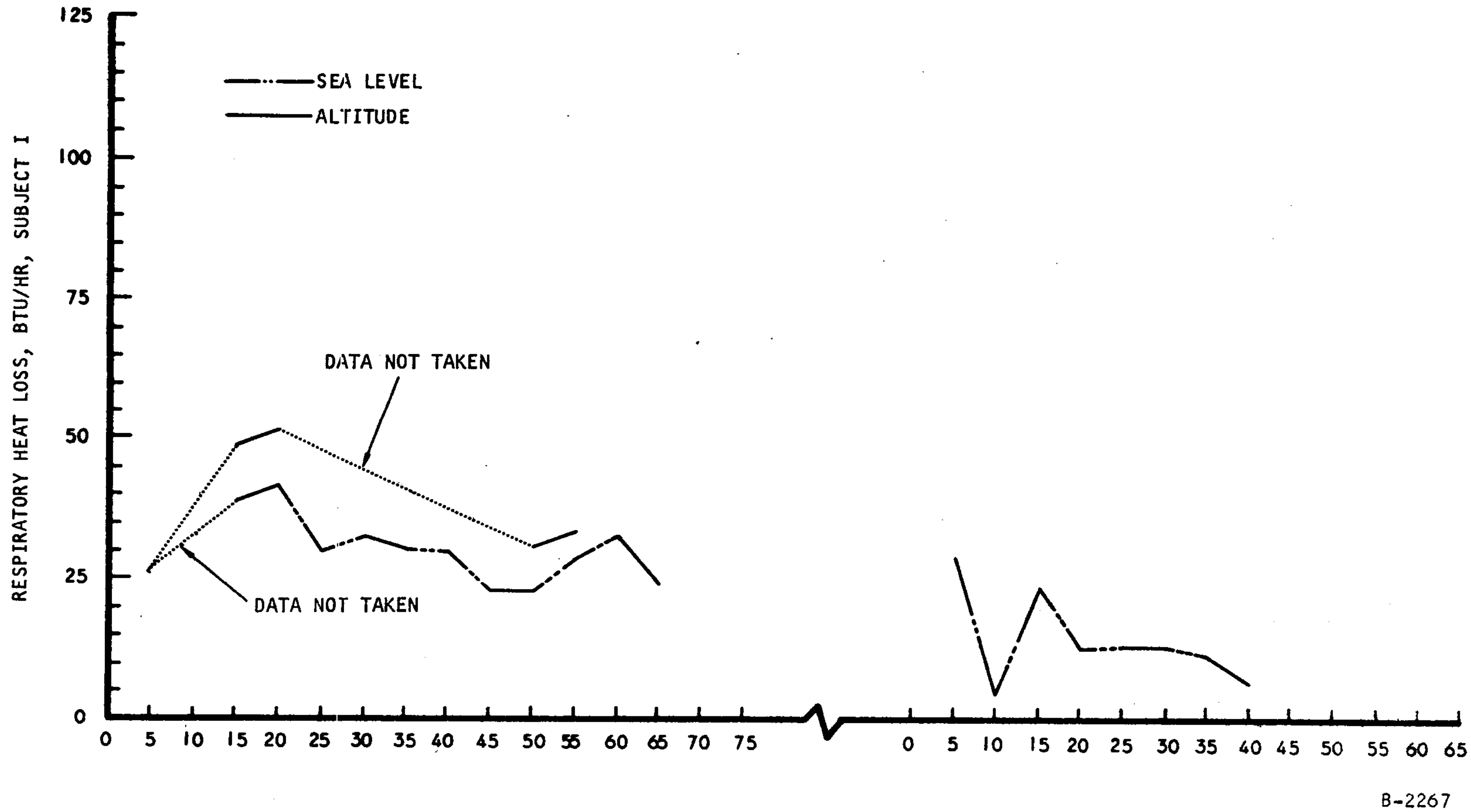


Figure 130. Respiratory Heat Loss, Subject I

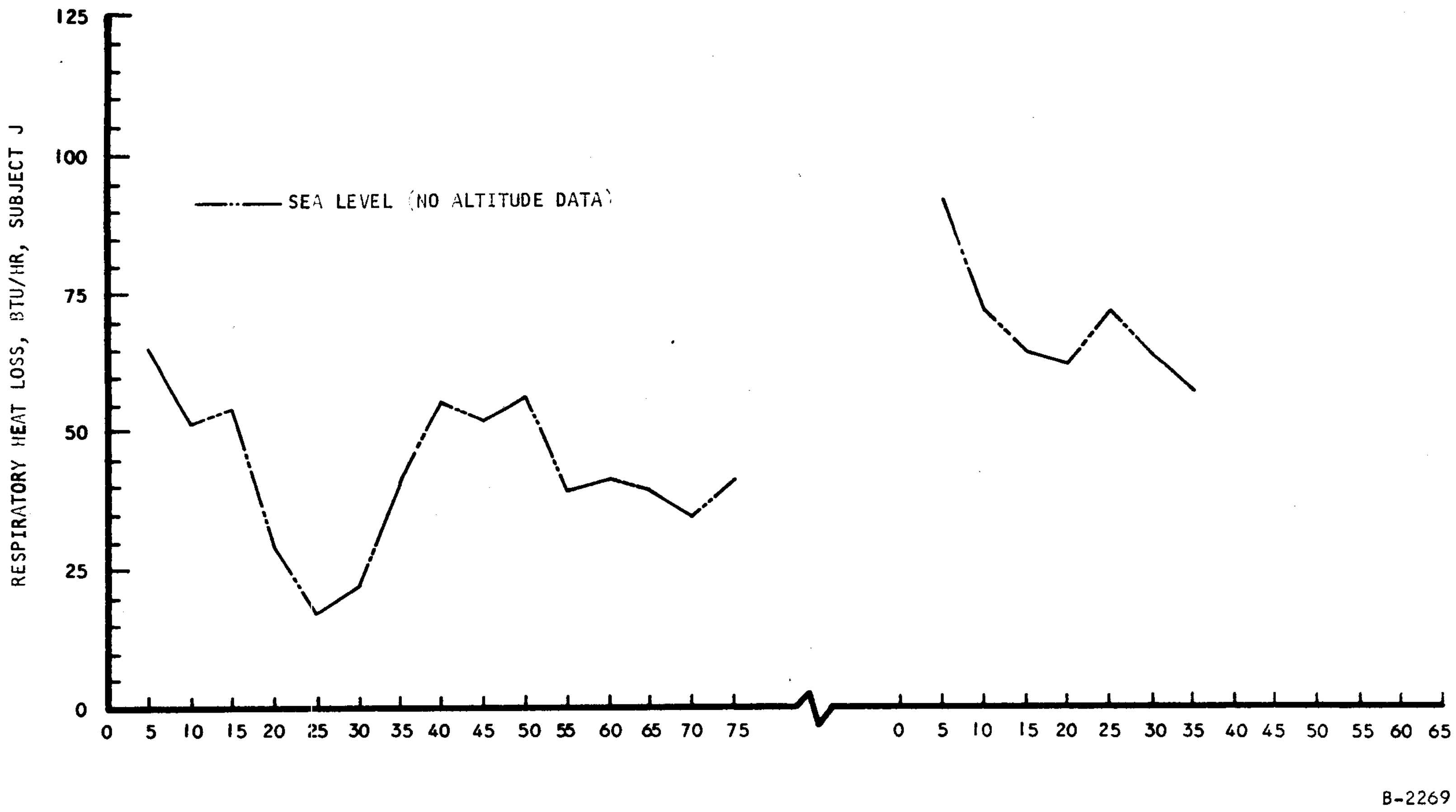


Figure 131. Respiratory Heat Loss, Subject J

RESPIRATORY WATER LOSS

Respiratory water loss for subjects in the pressurized suit ranged from -0.07 to approximately +0.75 gm/min. The average rate, however, was between 0.4 and 0.6 gm/min. The data (Figures 132 through 141) are presented for 5-min intervals, for sea level and altitude conditions, and for high and low activity levels. The latter are presented as the right and left graphs in each figure.

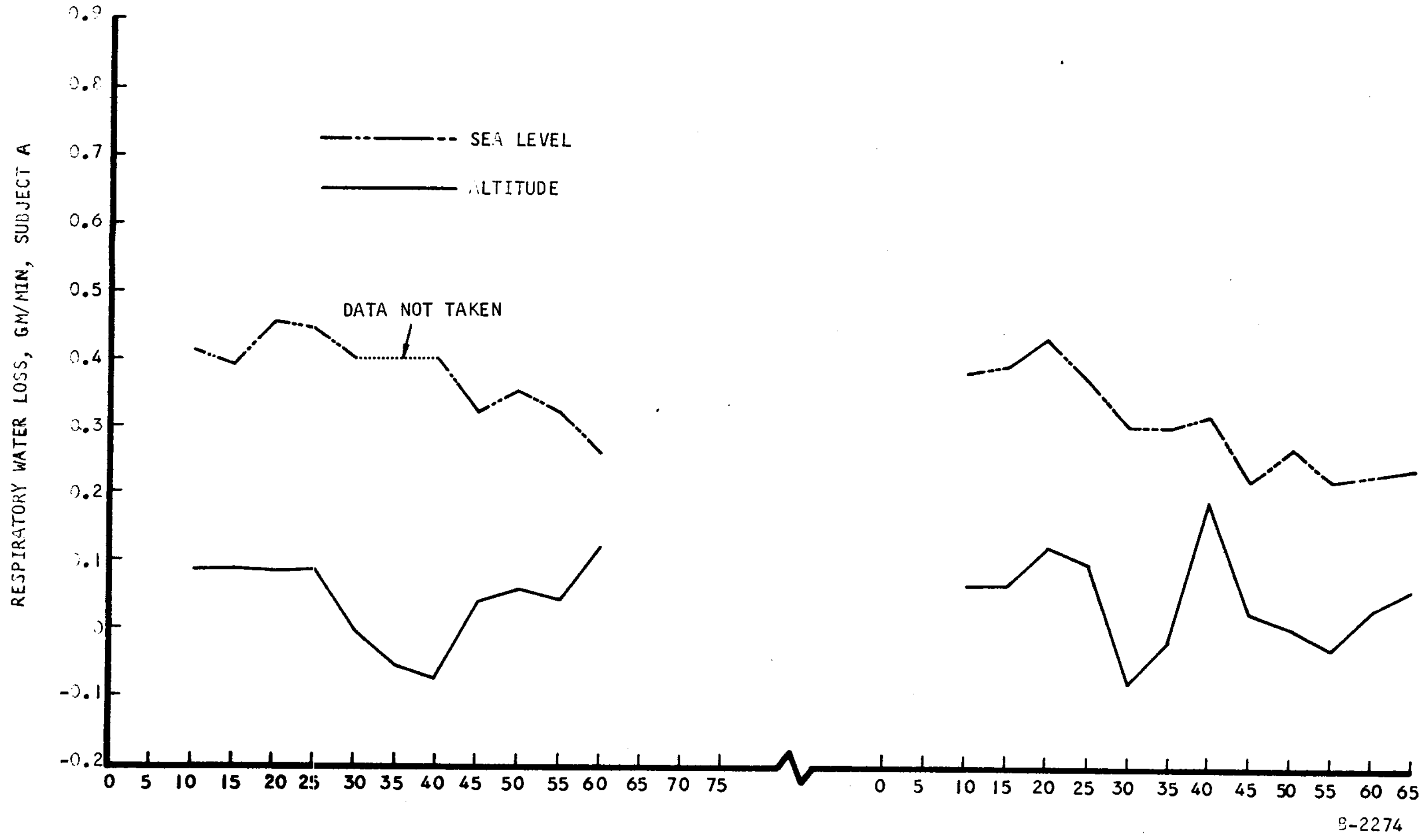


Figure 132. Respiratory Water Loss, Subject A

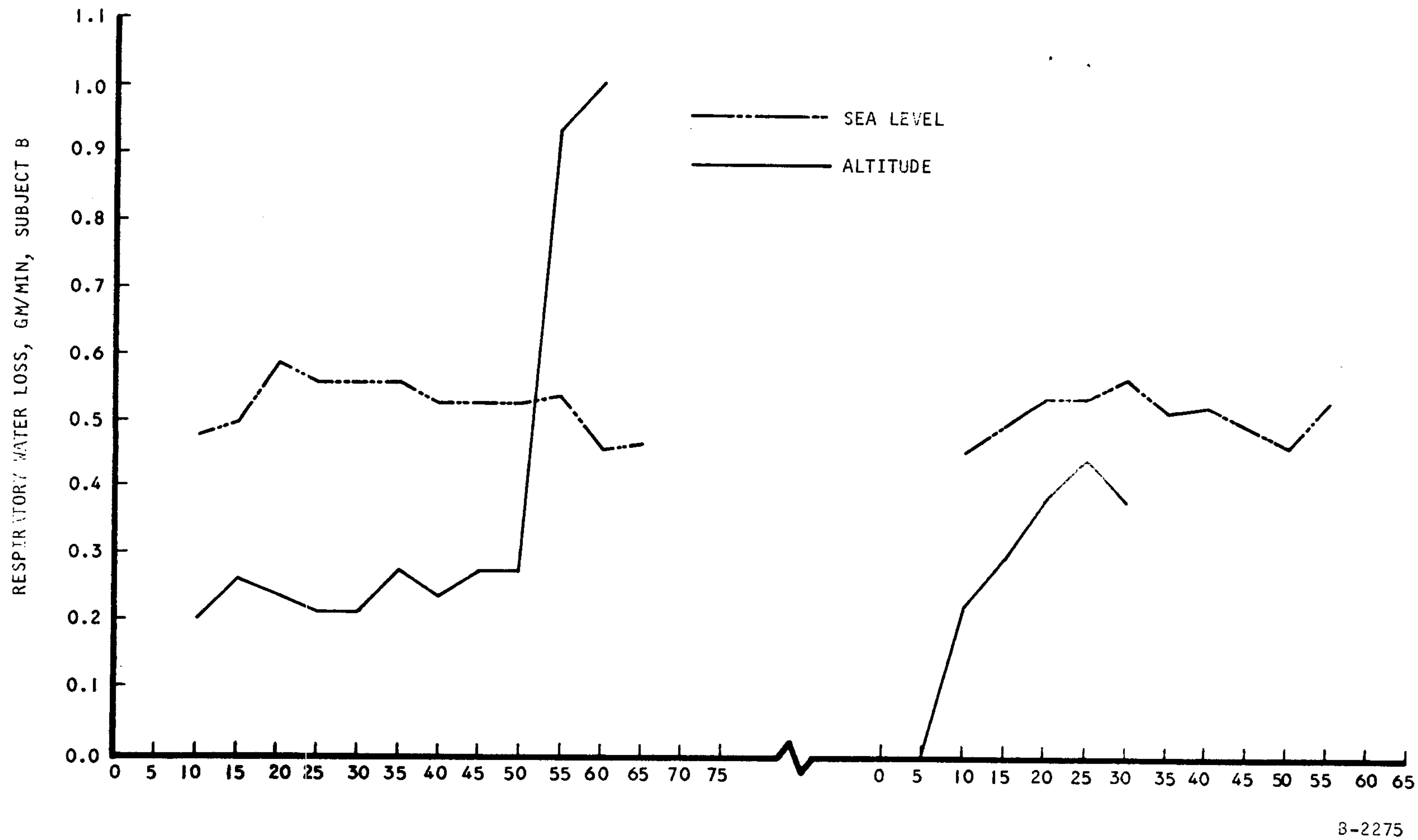


Figure 133. Respiratory Water Loss, Subject B

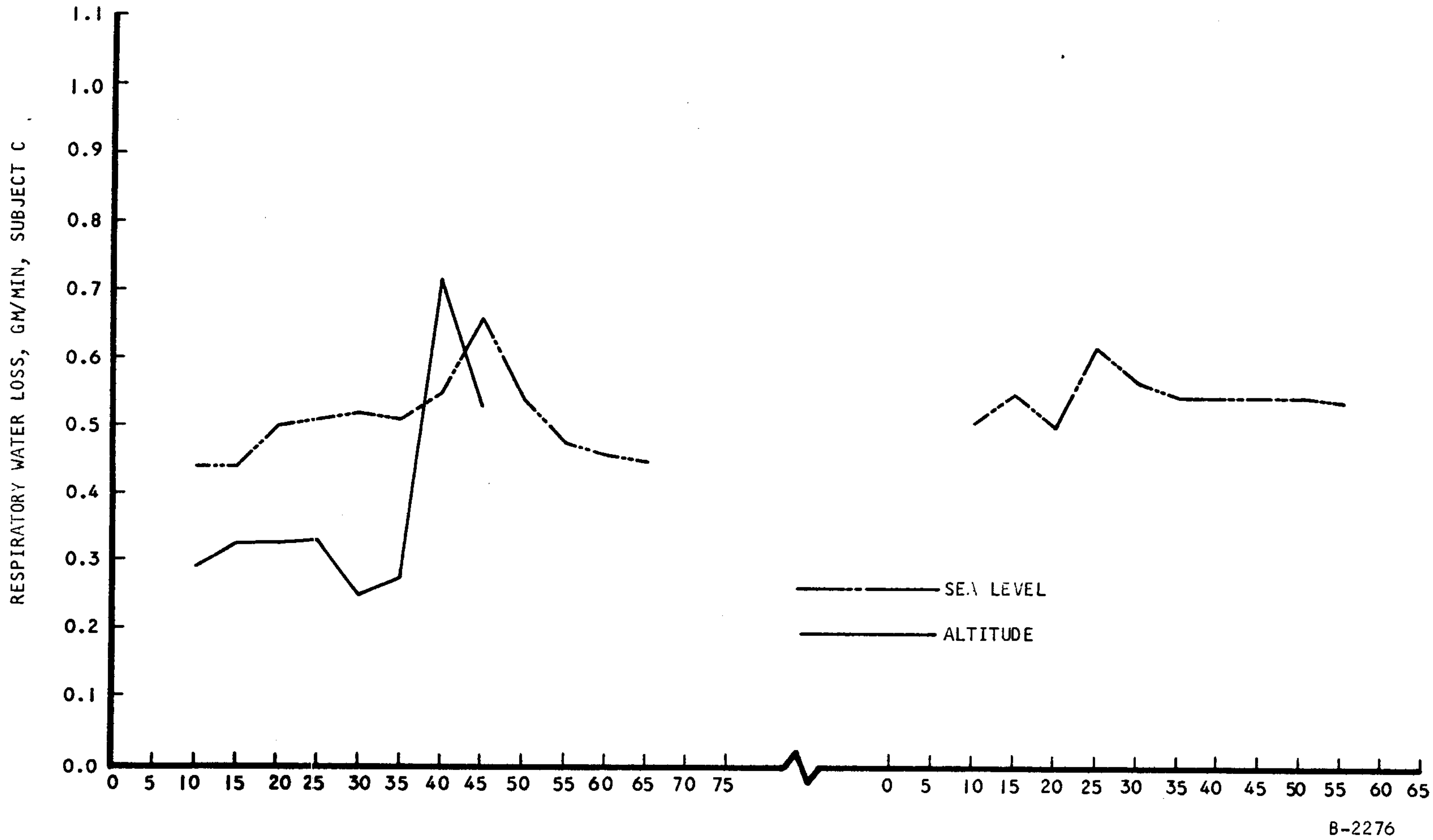


Figure 134. Respiratory Water Loss, Subject C

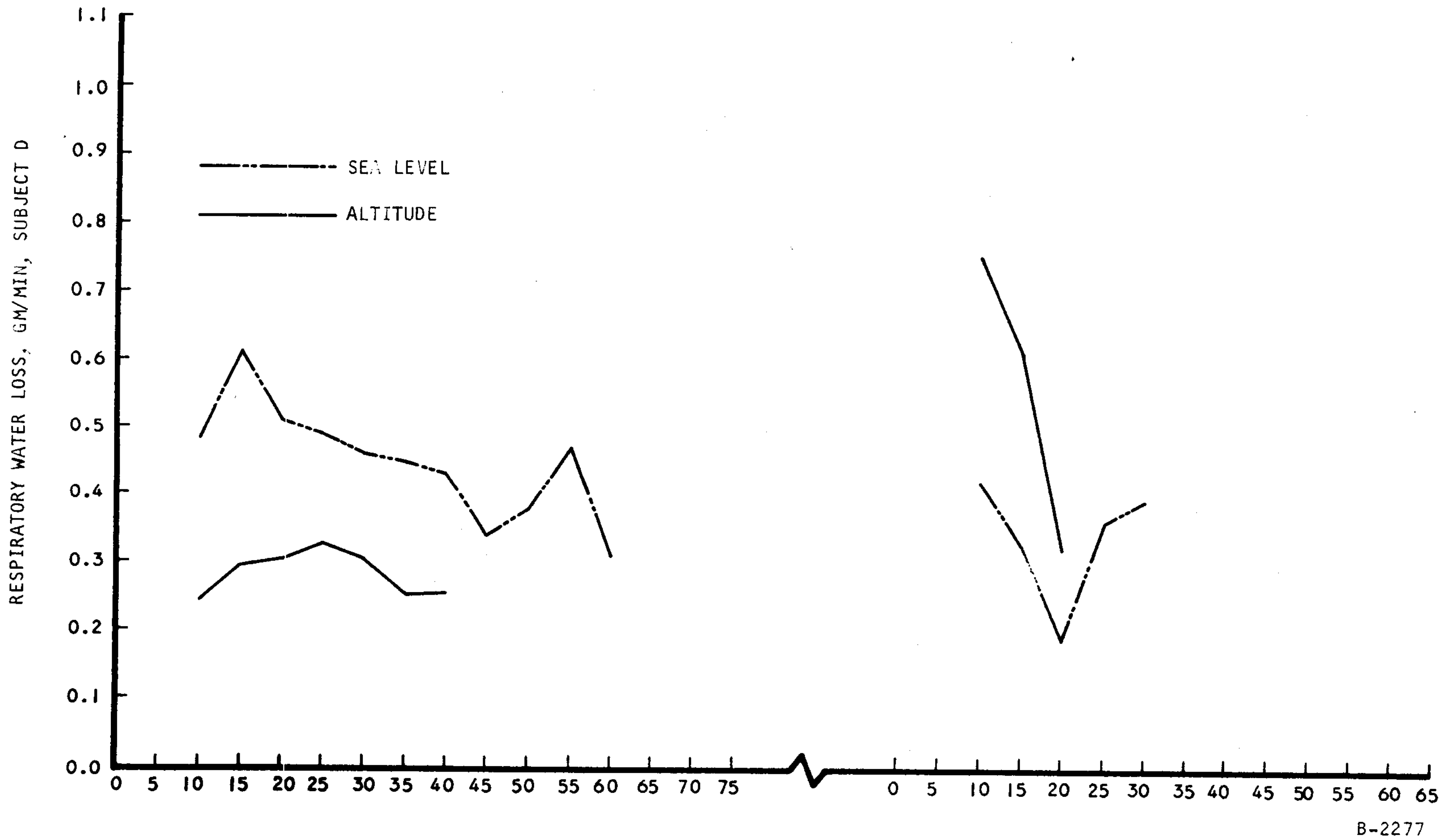


Figure 135. Respiratory Water Loss, Subject D

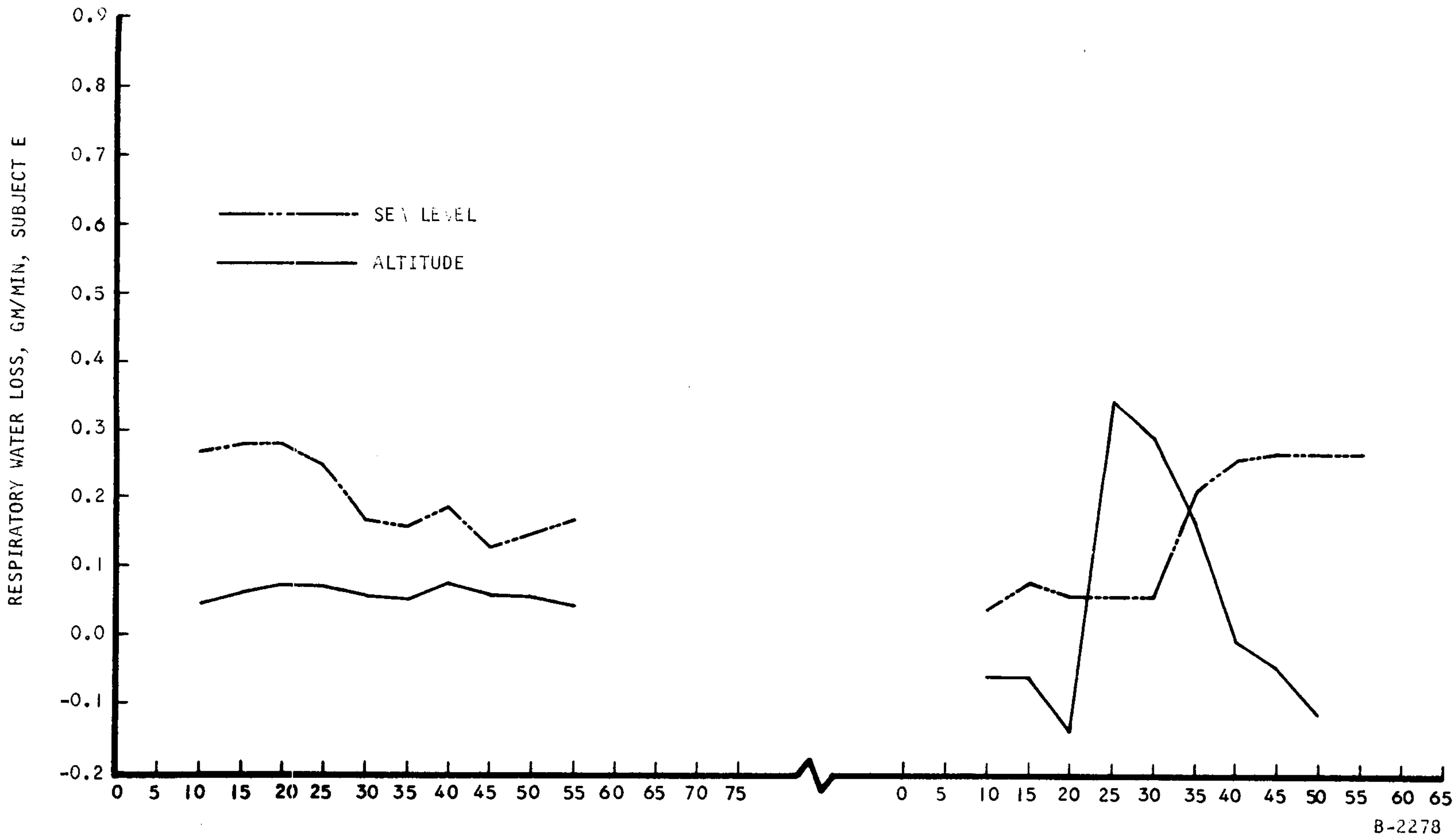


Figure 136. Respiratory Water Loss, Subject E

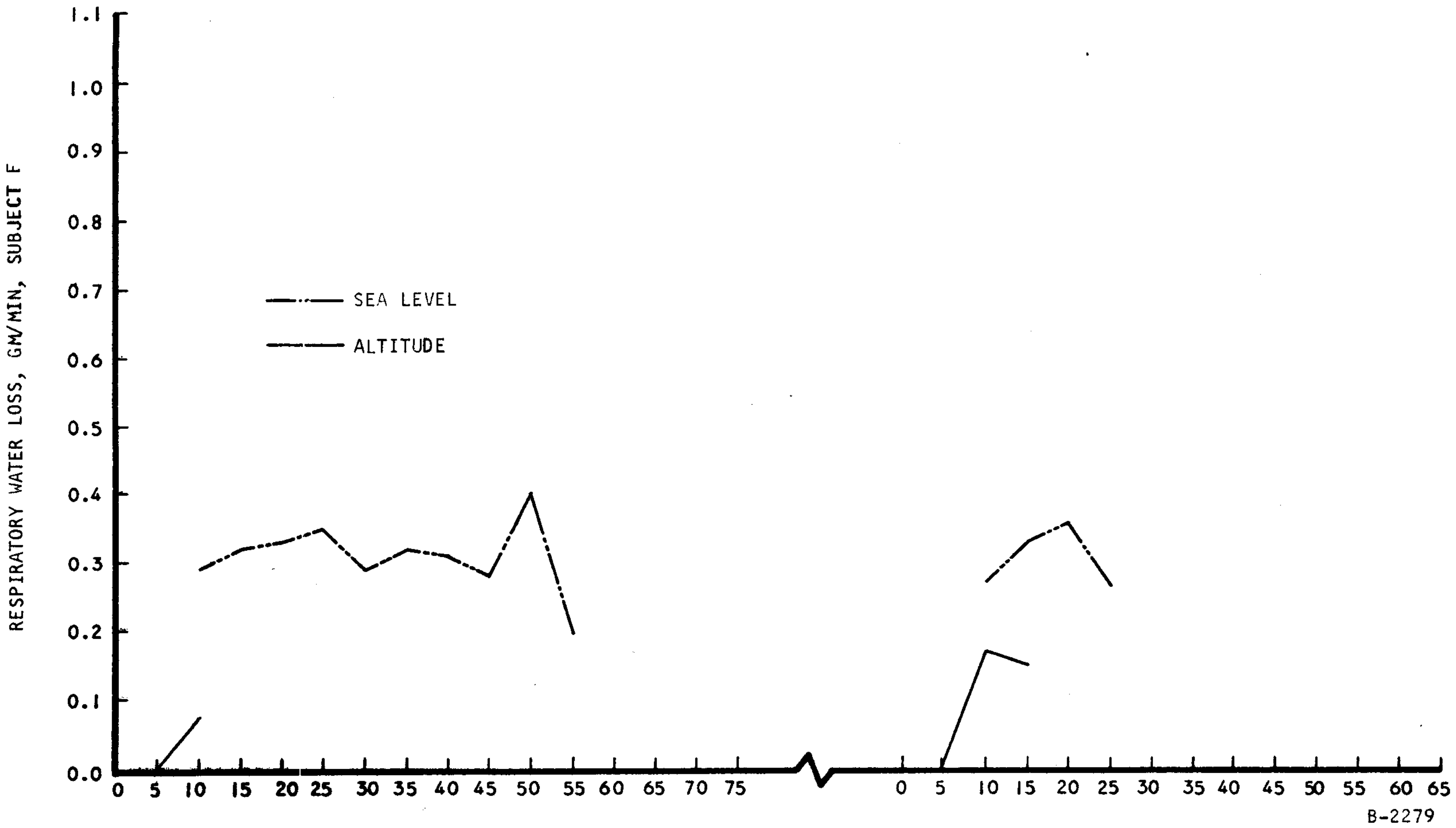


Figure 137. Respiratory Water Loss, Subject F

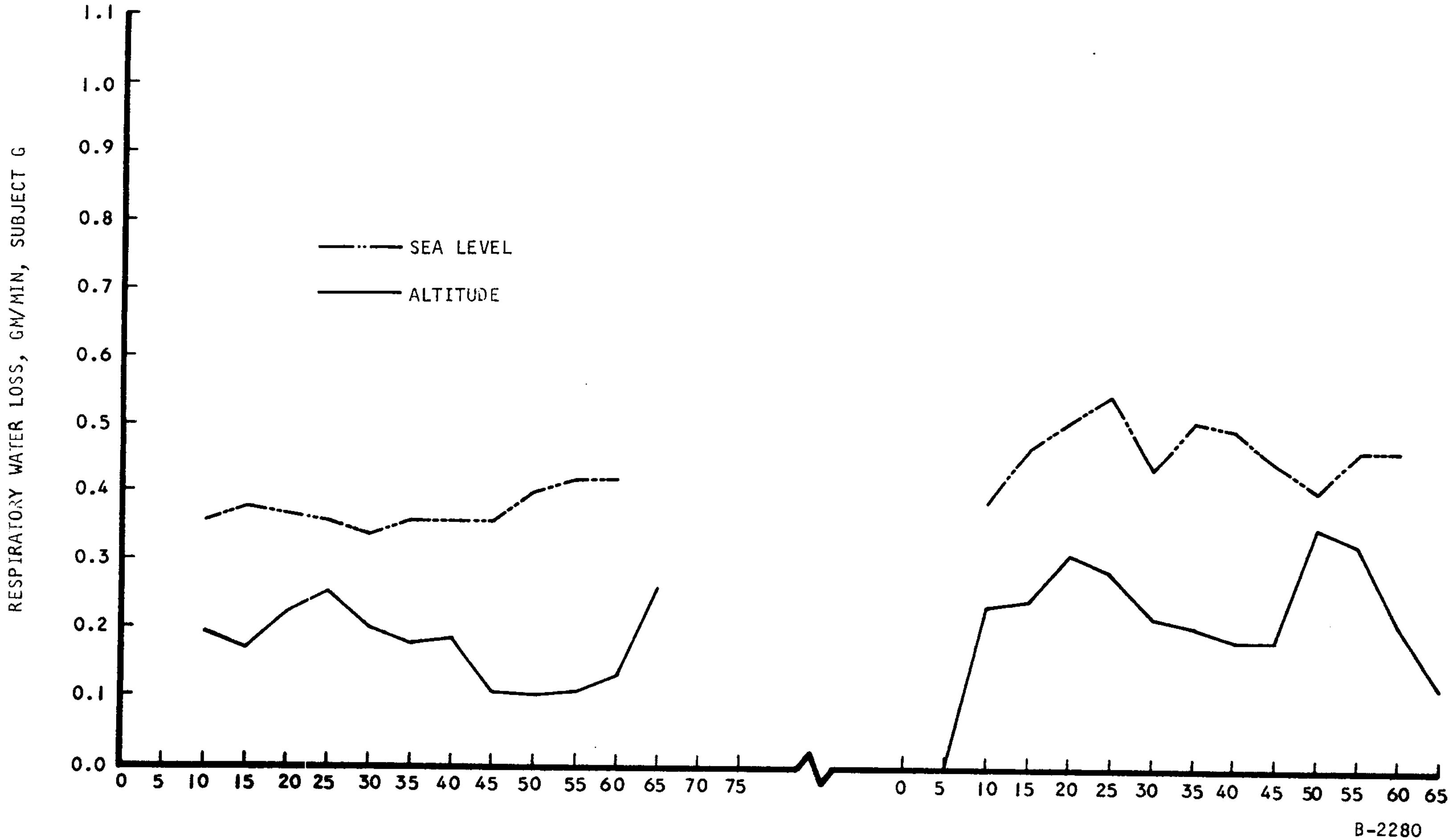


Figure 138. Respiratory Water Loss, Subject G

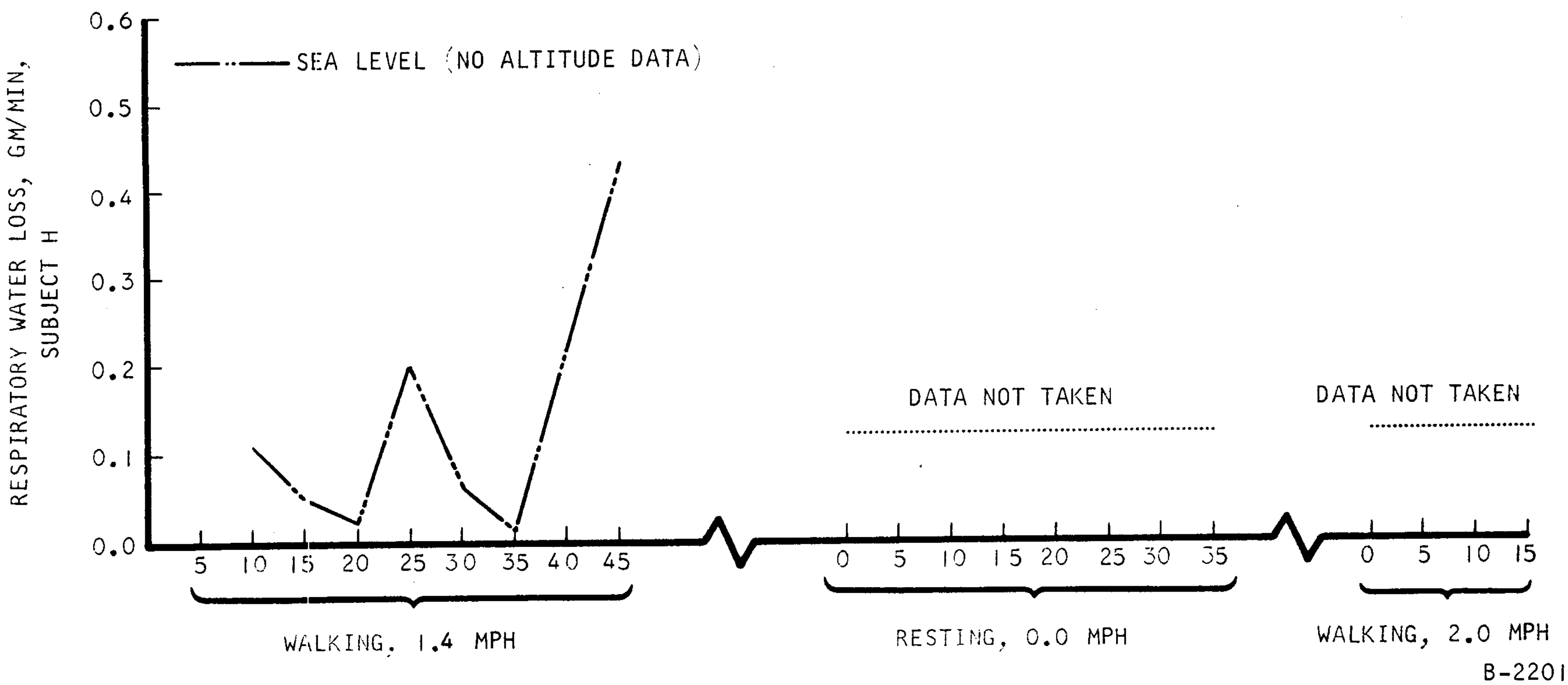


Figure 139. Respiratory Water Loss, Subject H

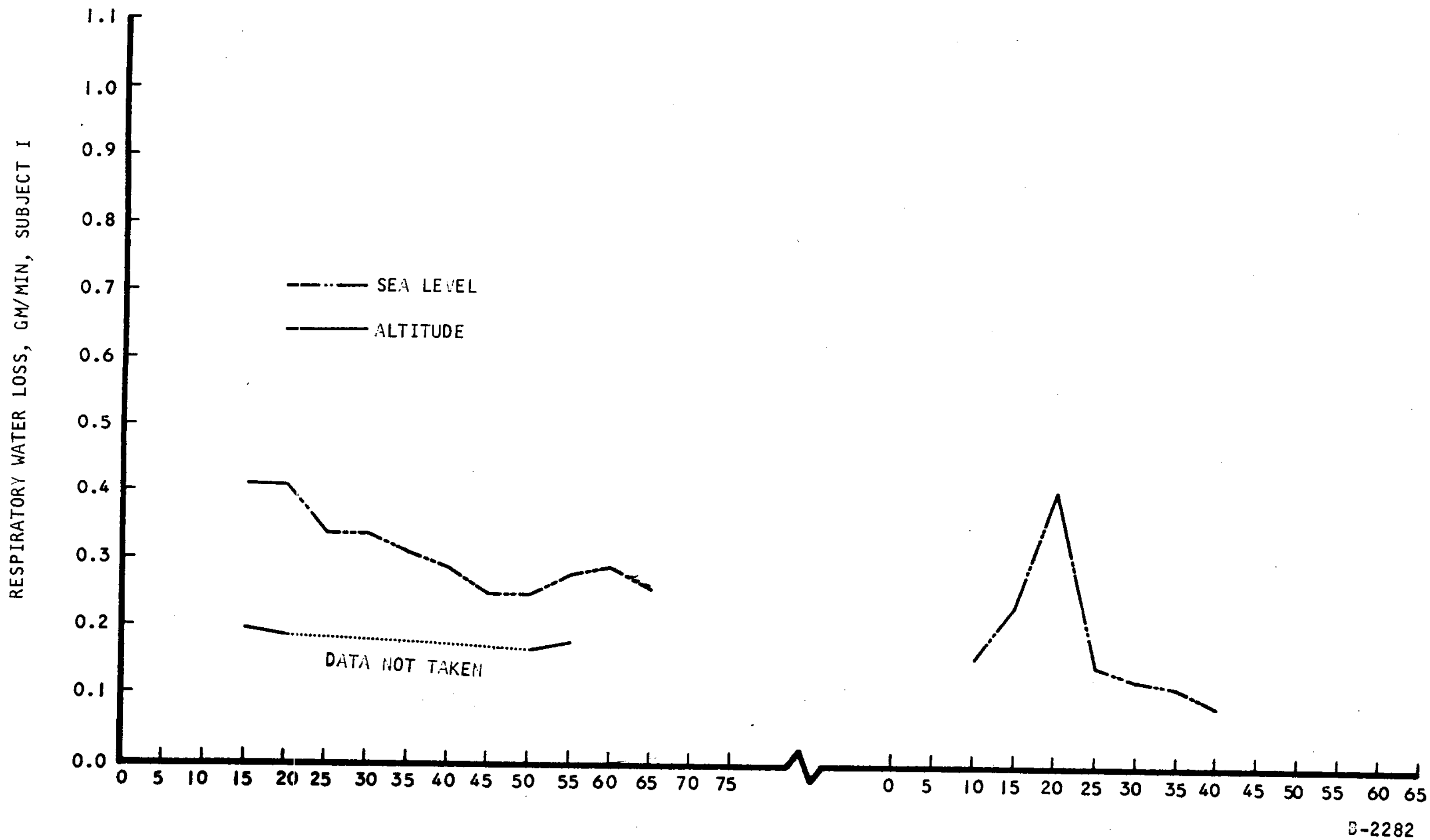


Figure 140. Respiratory Water Loss, Subject I

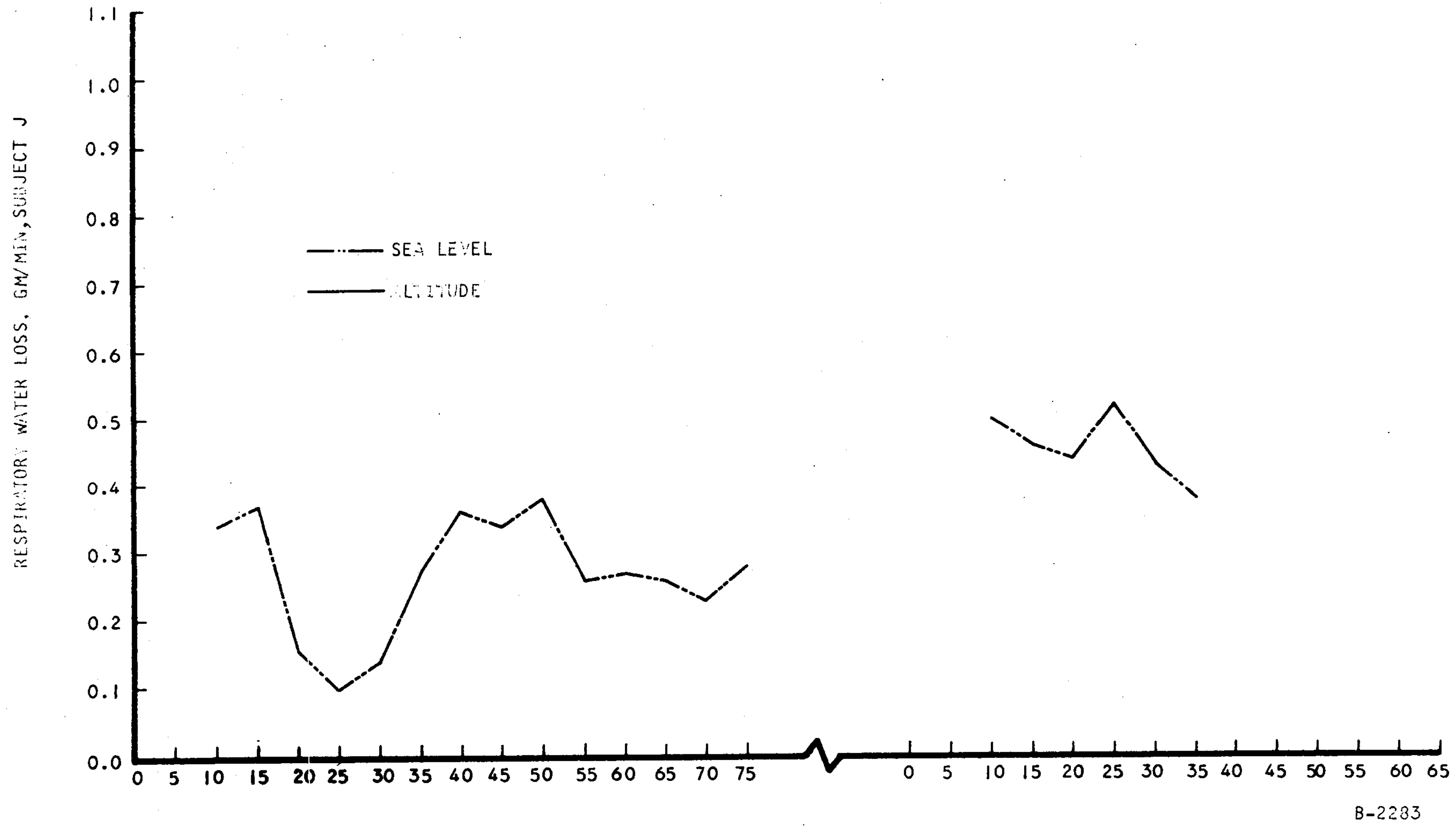


Figure 141. Respiratory Water Loss, Subject J

SECTION 7

DISCUSSION

The results of this experiment permit the evaluation of a heat balance that accounts for all of the heat generated, transferred, and stored during the experimental process of working in the pressurized Gemini G2-C suit. The form of such a heat balance for any particular test or for the average results of all the tests is as follows:

$$Q_M = Q_N + Q_S + Q_{work}$$

or

$$Q_M - Q_N - Q_S - Q_{work} = 0$$

where Q_M is the measured metabolic rate, Q_N is the net heat removal, Q_S is the rate of heat storage in the subject's body, and Q_{work} is the rate of heat being expended as useful work.

The metabolic rate (Q_M) was measured by methods discussed previously in this report. The net heat-removal rate (Q_N) was computed by subtracting the heat computed for pumping effects from the measured ventilation heat removal; Q_N represents that portion of the total heat removed that is generated by the subject's metabolism alone. The rate of heat storage (Q_S) and the rate of heat expended as work (Q_{work}) are difficult to measure and were not measured directly in this experiment, although a good estimate of Q_S can be made and will be discussed later in this section.

It is, of course, possible to set up heat balances for each subject at each data point using the equation above. For the purposes of discussion, it is more meaningful to examine the means for all of the subjects at the last data point in each mode; this provides a better understanding of the general characteristics of the pressure suit and of the physiological reactions of the subjects. Table 2 shows the mean final metabolic rates under the four conditions of work rate and pressure, and Table 3 shows the mean final net heat removal rates under these conditions. Subtracting the numbers in these tables, we obtain the following table, which contains values for $Q_M - Q_N$ $(= Q_S + Q_{work})$:

TABLE 13

MEAN FINAL STORED HEAT RATE PLUS HEAT OF WORK, BTU/HR

	Work Rate	
Pressure	1.4 mph	2.0 mph
Sea Level	716	1005
Altitude	906	1296

The heat rates shown in this table are the quantities that must now be accounted for. The rate of heat storage (Q_S) will be discussed first because it is a quantity that can be estimated directly, and because it is expected to be the more important of the two heat rates whose sums are shown in the table. As was mentioned earlier, a heat storage or heat storage rate computed from rectal temperature is unsatisfactory. The following paragraphs discuss body heat storage and the factors involved in its estimation.

Heat storage in the body during exercise is a major factor in establishing heat balance, i.e., the achievement of equilibrium between the storage of heat, metabolic rate, and work, and the removal of heat by convection, evaporation, and radiation. Stored heat normally is computed from changes in mean body temperature as defined by average skin temperature and core temperature. The method of determining mean body temperature varies in terms of site and number of temperature measurements taken, and in the assigned theoretical contribution of a given area to the total temperature. Nevertheless, all mean body temperatures computed by this method have been shown to be systematically too low in cold environments, indicating a larger heat loss than is the actual case (References 9 and 10). Furthermore, calculations utilizing this method show that the opposite condition prevails in hot environments; i.e., the computed heat storage is less than actual (Reference 10). The method is also inadequate when equilibrium conditions do not exist (Reference 11).

A variation in experimental procedures that has a significant effect on heat storage is the method by which heat is applied. Many investigators maintain the subject at rest while changing his environment by increasing or decreasing the ambient temperature. Under these conditions, the temperature gradients are entirely different from those found when the subject is exercising or when the ambient temperature is maintained constant.

It has been reported (Reference 12) that the temperature in the muscles of the leg during heavy exercise can increase as much as 11°F. Esophageal temperature, heart rate, and systolic pressure all rise concurrently, then level off and remain constant for the remainder of the exercise, although rectal temperature rises steadily and shows no tendency to level off, even an hour after exercise has terminated. These observations suggest that physiological parameters that change at similar rates during changes in temperature might be profitably used in estimations of heat storage. This is an important consideration because direct measurement of temperature in muscle is impractical in most situations, and because experimentally determined weighting factors necessary for heat storage calculations for nonsteady states are unavailable.

The skeletal muscle mass of the human body comprises 42 to 50 percent of the total body weight. At rest, the temperature of these muscles is lower than rectal temperature, but during exercise the rise in muscle temperature is from 2 to 4 times greater than that of the rectum or esophagus. Consequently, any core temperature computed from rectal temperature, or from rectal temperature averaged with skin temperature, during exercise could not give a mean body temperature equivalent to actual temperature.

The heat stored in the body is determined generally by the following equation:

$$Q_S = WC_p\Delta T \text{ Btu}$$

where W = body weight in pounds

C_p = specific heat of the mass in Btu/lb-^{0}F. The value of 0.83 is generally used for average body specific heat; the specific heat of muscle is approximately 0.86 (Reference 13)

ΔT = average temperature change of the mass

Figure 142 shows the heat stored as a function of muscle masses and temperature changes.

The muscles used and the extent of usage are a function of the particular exercise being done. Pedaling an ergocycle exercises the leg muscles, while the arms, shoulders, and back muscles are used to a lesser extent. Normal walking exercises the legs to a greater extent than it does the other muscles. Walking in a pressurized suit, however, requires the use of considerably more muscles than does normal walking because of the peculiar gait required to overcome the resistance of the pressure suit and to maintain balance.

The test conditions of this program required a very high degree of muscular involvement due to the high work rates, the increased muscular usage to compensate for fatigue in the primary muscles, the restrictions imposed by the small size and constant rate of the treadmill, the maintenance of the position of the head (helmet) in a relatively small volume because of the restrictions of the respiration system, and the fit of the suit (no subject was completely comfortable in all respects).

The following example is presented as a quantitative illustration of total body heat storage under assumed conditions. The assumptions are based

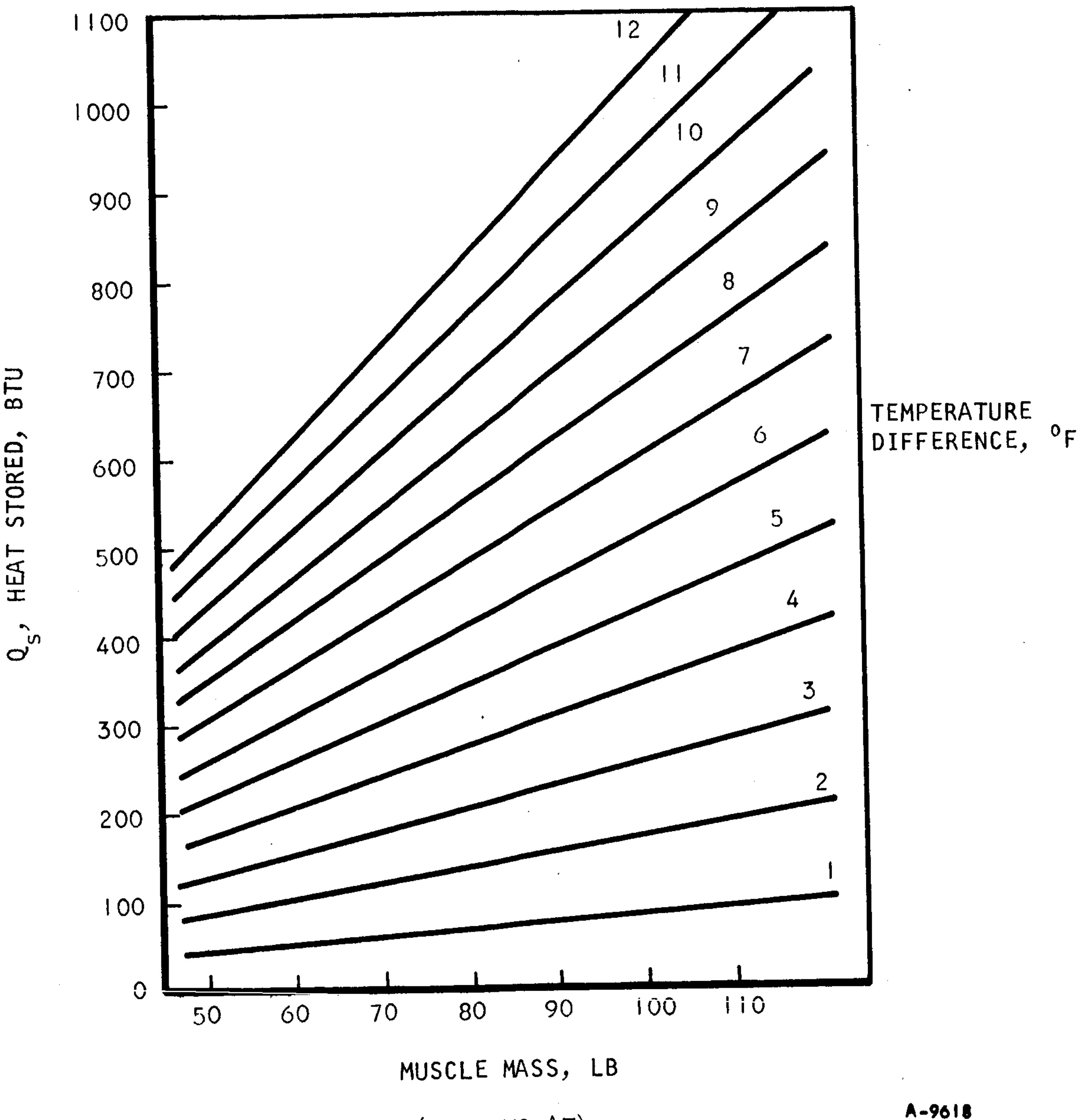


Figure 142. Heat Storage in Muscle

on the preceding discussion, and the physiological and thermal parameters used in this illustration represent approximate averages of the characteristics of the subjects and the means of the appropriate test data. These assumptions are:

Total body weight = 145 lb

Skeletal muscle mass (W_m) = 61 lb (42 percent of body weight)

Remaining or net body mass (W_n) = 84 lb

Rectal temperature increase per hour (T_r) = $3^{\circ}F$

Skeletal muscle temperature increase (T_m) = $5^{\circ}F$, $7^{\circ}F$ and $10^{\circ}F$

Skeletal muscle heat capacity (C_m) = 0.86 Btu/lb-$^{\circ}F$

Net body mass heat capacity (C_n) = 0.83 Btu/lb-$^{\circ}F$

The heat storage figure will include the sweat transpired but not evaporated during the test.

The rectal temperature increase may be used to represent the temperature increase of the net body mass (T_n).

The equation for body heat storage is

$$Q_S(\text{average}) = W_m C_m T_m + W_n C_n \Delta T_n \text{ Btu}$$

$$= W_m C_m T_m + W_n C_n \Delta T_r \text{ Btu}$$

and thus

$$Q_S = (61 \times 0.86 \times \Delta T_m) + (84 \times 0.83 \times 3) = 52.5\, \Delta T_m + 209$$

Substituting $5^{\circ}F$, $7^{\circ}F$, and $10^{\circ}F$ for ΔT_m, we obtain, respectively,

$$Q_S(\text{average}) = 471,\ 576,\ \text{and}\ 735 \text{ Btu}$$

If we assume that 50 percent of the total body weight is skeletal muscle, the respective heat storage values become

$$Q_S(\text{average}) = 521,\ 646,\ \text{and}\ 833 \text{ Btu}$$

If the rectal temperature increased by $4^{\circ}F$ instead of $3^{\circ}F$, then the heat storage values for the three values of ΔT_m would be:

$$Q_S(\text{average}) = 591,\ 716,\ \text{and}\ 903 \text{ Btu}$$

The muscle temperatures at the end of each test in this program would tend toward the upper limits, since the subjects were completely exhausted at termination. The percentage of muscle for each subject was not measured, but it varied between subjects. For example, two subjects were quite muscular and in very good physical condition. In these subjects, the percentage of muscle would be high, and the heat storage during the test could be as much as 1000 Btu.

It is now possible to make estimates to supply the missing quantities in the heat balance equation; i.e., the rate of heat storage in the body (Q_S) and the rate of heat expended as physical work (Q_{work}). Heat expended as useful work is generally discussed in terms of "efficiency," which is the percentage of the metabolic heat used for work, and hence not recoverable from the environment by means of ventilation gas flow. The maximum efficiency of working human beings is about 22 percent. For the purpose of making a heat balance using the mean end-of-run data, this discussion will employ the average test length of 1 hr per mode, so that Q_S, the heat storage rate, may also be considered the total heat storage, as was done in the example above.

The average subject weight was 145 lb, and the approximate rectal temperature rise was $2^{\circ}F$ in each mode. As in the example, we will assume that rectal temperature adequately reflects the temperature of the body mass, excluding skeletal muscle. The heat storage depends also on the quantity (weight) of skeletal muscle, and this quantity can vary between approximately 40 and 50 percent in normal subjects. We will assume that the mean percentage of skeletal muscle in our subjects was 40 percent; this figure appears reasonable and also will result in a comparatively conservative estimate.

With these factors fixed, the equation for stored heat becomes

$$Q_S = 52.46\ \Delta T_m + 139.44$$

where ΔT_m is the mean elevation in the temperature of the skeletal muscle mass. The equation for efficiency is, similarly

$$\text{Efficiency} = \frac{Q_{work}}{Q_M} \times 100 = \frac{(Q_M - Q_N - 52.46\ \Delta T_m - 139.44)100}{Q_M}$$

where Q_M is the mean end-of-run metabolic rate (see Table 2). Either Q_S or efficiency can be computed by assuming one of the terms and knowing the mean sum of Q_S and Q_{work} from Table 13. In other words, to complete the heat balance we can either assume a mean muscle temperature elevation in each of the four modes (thus assuming a stored heat quantity) and compute the efficiencies, or we can assume efficiencies (and thus Q_{work}) and compute the quantities of heat storage. This relationship between efficiency and heat storage, as observed in the averaged data, is shown by Figure 143, which

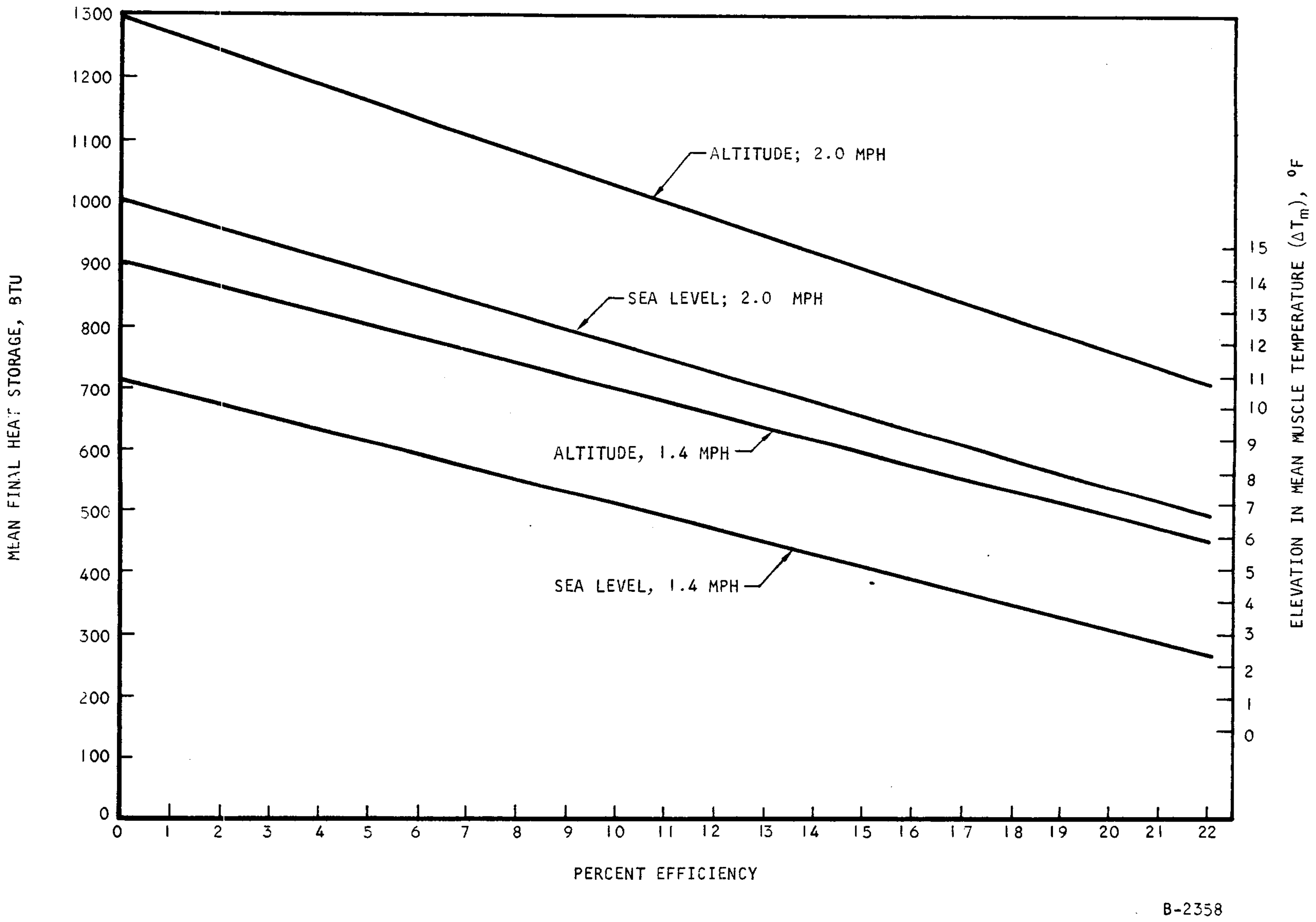


Figure 143. Heat Storage and Efficiencies Required for Heat Balance

depicts four lines, one for each condition. This figure is a plot of skeletal muscle temperature elevation (ΔT_m), and the concomitant heat storage (Q_S), against efficiency.

From this figure, it is possible to examine various combinations of efficiencies and heat storages. For example, a 10°F mean value for ΔT_m appears reasonable for consideration in all of the modes; this value corresponds to a heat storage during one hour of 664 Btu, and efficiencies of 2.5, 11.6, 14.5 and 23.4 percent for the sea level, 1.4 mph; altitude, 1.4 mph; sea level, 2.0 mph; and altitude, 2.0 mph modes, respectively. Another reasonable figure for efficiency is 17 percent, which leads to heat storages of 368, 550, 606, and 836 Btu for these respective modes. It is unrealistic, however, to consider that either the heat storage or the efficiency is the same in different modes. It would appear from Figure 143 that the high work rates (2.0 mph) are more efficient than the lower work rates, and that altitude or, more probably, increasing subject fatigue also results in increases in efficiency and stored heat. The hypothesis that the higher work rate resulted in higher efficiency was not weakened by visual observations of the subjects' struggles to keep upright and abreast of the treadmill at these rates (recall that this measure of "efficiency" is the exact opposite of walking efficiency).

The graphs of Figure 143 complete the heat balance for the mean end-of-runs data collected in this experiment. One primary assumption used in this computation was that radiative and convective heat loss or gain from the surface of the suit was zero or negligible. It is worthwhile in this discussion to justify this assumption and to examine the question of nonventilatory heat loss in some detail. The following paragraphs present a discussion of the question of heat transfer through the pressure suit wall.

Control of heat leakage from the Gemini suit by radiation and convection was obtained by maintaining constant and elevated tank-wall and ambient-air temperatures, and by enclosing the suit in a multilayer reflective garment.

The effect of varying the ambient temperature on radiation heat transfer is illustrated by the following equation:

$$Q_R = \sigma F A (T_{suit}^4 - T_{ambient}^4)$$

where σ = 0.1712×10^{-8} Btu/hr-ft^2-$^{\circ}$R, Stefan-Boltzmann Constant

F = "view" factor, which is determined by the surface areas, geometries, and emissivities; for our application this factor will range from 0.5 to 1.0

Q_R = radiation heat loss

If the simplifying assumptions are made that the suit can be represented by a small sphere within a large sphere representing the cabin, then the equation can be reduced to

$$Q_R = \varepsilon_1 A_1 (T_1 - T_2)$$

where ε_1 = emissivity of the suit

A_1 = surface area of the suit

T_1 = the temperature of the suit

T_2 = the temperature of the cabin

The advantage of these assumptions is that the geometry does not influence Q_R. The approximations that will be used for the actual geometry are as follows:

$$F = \varepsilon_1 F'$$

where $F' = 0.7$ and $\varepsilon_1 = 0.5$

$A_1 = 32.4$ sq ft

The surface temperature of the suit (T_{suit}) varies to some extent because of ambient temperature changes. Previous experiments in our laboratory indicate that the suit ventilating gas outlet temperature provides a fairly good value for the suit surface temperature. An additional factor to account for radiation from skin to the suit inner lining can also be considered when required. For this discussion, the T_{suit} will be assumed to be 90°F or 550°R. Therefore, the following equation can be set up, with $T_{ambient}$ representing the variable whose effect is to be examined; that is, the ambient gas and cabin wall temperatures.

$$Q_R = 0.1712 \times 10^{-8} \times 0.7 \times 0.5 \times 32.4\ (550^4 - T_{ambient}{}^4)$$

Because the terms of the equation have been reduced to Q_R and $T_{ambient}$, the partial differential can be taken

$$\frac{\rho Q_R}{\rho T_{ambient}} = K\ (4\ T_{ambient}{}^3)$$

where $K = 0.1712 \times 0.7 \times 0.5 \times 32.4 \times 10^{-8} = 1.94 \times 10^{-8}$

therefore

$$\Delta Q_R = 1.94 \times 10^{-8} \times 4 \times T_{ambient}^{3} \times \Delta T_{ambient}$$

giving the difference equation

$$\Delta Q_R = 7.76 \times 10^{-8} T_{ambient}^{3} \times \Delta T_{ambient}$$

If it is assumed for the initial conditions that $Q_R = 0$,

then

$$T_{ambient} = 550^{0}R$$

and

$$\Delta Q_R = 7.76 \times 10^{-2} \times (\frac{550}{100})^{3} \times \Delta T_{ambient} = 12.9 \Delta T_{ambient} \text{ Btu/hr}$$

or

$$Q_R = 12.9 \text{ Btu/}^{0}\text{F - hr}$$

If a $\Delta T_{ambient} = 30^{0}F$ is considered as an example,

then

$$Q_R = 12.9 \times 30 = 387 \text{ Btu/hr.}$$

Convective heat transfer is affected by ambient temperature changes according to the following equation:

$$Q_{conv} = h_m A (T_{suit} - T_{ambient})$$

where h_m is the natural heat convection for vertical plates and A again is the suit area. Abbreviating the term $(T_{suit} - T_{ambient})$ as ΔT, the following assumption may be made:

$$h_m = 0.3 \Delta T^{0.25}$$

This assumption is sufficient for temperature differences from 0 to $30^{0}F$ when no ambient air current is present. Then, substituting:

$$Q_{conv} = 0.3A(\Delta T)^{0.25} (\Delta T)$$

$$= 0.3A\Delta T^{1.25}$$

The partial difference equation for this expression is very sensitive to variations in temperature because h_m is also a function of temperature differences. To demonstrate this, the following point calculations should be examined:

$$h_m(\Delta T = 10) = 0.3 \times 1.778 = 0.5334$$

$$h_m(\Delta T = 20) = 0.3 \times 2.12 = 0.636$$

$$h_m(\Delta T = 30) = 0.3 \times 2.34 = 0.702$$

$$Q_{conv}(\Delta T = 10) = 0.533 \times 32.4 \times 10 = 173 \text{ Btu}$$

$$Q_{conv}(\Delta T = 20) = 0.636 \times 32.4 \times 20 = 413 \text{ Btu}$$

$$Q_{conv}(\Delta T = 30) = 0.702 \times 32.4 \times 30 = 683 \text{ Btu}$$

To determine the total loss at -10^oF, -20^oF, -30^oF, the following equation is used:

$$Q_{conv} + Q_{rad} = Q_T \text{diff}$$

thus

$$T_{suit} = 80^oF, \; Q_T = 173 + 129 = 302 \text{ Btu}$$

$$T_{suit} = 70^oF, \; Q_T = 413 + 258 = 671 \text{ Btu}$$

$$T_{suit} = 60^oF, \; Q_T = 683 + 387 = 1070 \text{ Btu}$$

As stated previously, the temperature of the suit surface will generally not be a constant; it will vary as the overall heat transfer coefficient varies.

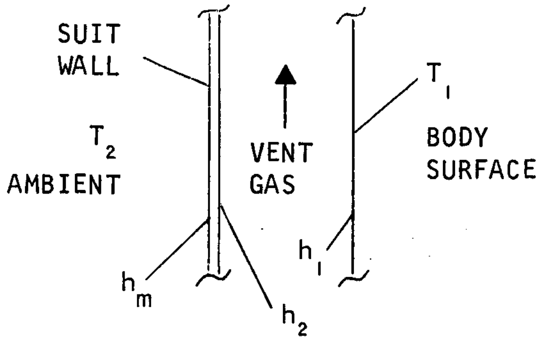
The effect of varying ambient conditions on convective cooling is also of considerable importance. The convective heat transfer coefficient is determined by the following equation:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_m}$$

where h_1, h_2, h_m are film coefficients as shown below. The other quantities, conduction and radiation, being neglected, and assuming $h_1 = h_2 = 4$, for slow-moving air, then:

$$\frac{1}{U} = \frac{1}{4} + \frac{1}{4} + \frac{1}{h_m}; \; 0 \leq h_m < 0.702, \text{ (generally), as computed}$$

above.



$$\frac{1}{U} = \frac{1}{2} + \frac{1}{h_m}$$

$$U = \frac{2\,h_m}{h_m + 2}$$

$$U(\Delta T = 10) = \frac{2(0.5334)}{2.5334} = 0.422$$

$$U(\Delta T = 20) = \frac{2(0.636)}{2.636} = 0.482$$

$$U(\Delta T = 30) = \frac{2(0.702)}{2.702} = 0.520$$

$Q = UAT$ (Convective heat transfer)

$$Q_{(\Delta T = 0)} = 0$$

$$Q_{(\Delta T = 10)} = 0.422 \times 32.4 \times 10 = 137 \text{ Btu}$$

$$Q_{(\Delta T = 20)} = 0.482 \times 32.4 \times 20 = 312 \text{ Btu}$$

$$Q_{(\Delta T = 30)} = 0.52 \times 32.4 \times 30 = 505 \text{ Btu}$$

$Q_{T_{\Delta T}} = Q_{conv} + Q_{rad}$ (Total heat transfer by convection and radiation)

Using the same value of Q_{rad} as previously computed, then:

$$Q_T(\Delta T = 10) = 137 + 129 = 366 \text{ Btu/hr}$$

$$Q_T(\Delta T = 20) = 312 + 258 = 560 \text{ Btu/hr}$$

$$Q_T(\Delta T = 30) = 505 + 387 = 892 \text{ Btu/hr}$$

A comparison of these values to those previously computed above shows that examining the effects of a single variable without regarding the interaction of other variables can lead to erroneous values or conclusions.

These latter values are still based on over-simplified assumptions, but they are helpful here in that they illustrate the sensitivity and the complexity of investigation that is brought about by permitting large variations to occur in the ambient thermal and atmospheric conditions. Even with more sophisticated simplifying techniques and assumptions, a slightly more adequate computation would still produce an error of ±10 percent and would, practically, require laborious computer operations involving lengthy successive approximations. This discussion should demonstrate the importance of maintaining ambient temperatures constant and at the approximate temperature of the external portion of the suit. In this experiment, careful controls were exercised to ensure that the ambient temperature remained constant and that no moving air currents were present. In addition, a multilayer reflective garment was worn over the suit itself to further minimize errors. As a result of these precautions, errors from these sources are so small that a theoretical estimate other than zero heat transfer through the suit cannot be made.

One primary objective of this experiment was to determine if the proper manipulation of sea level conditions could adequately simulate altitude conditions. It was found that such sea level simulation was feasible in some aspects, and was not in others; reference should be made in this respect to the mean "end-of-run" data points in Section 6. In particular, it was found that by using a gas ventilation gas flow of 17.1 cfm, a suit-to-ambient pressure differential of 3.7 psig, a gas dew-point temperature of 33°F, and a gas dry-bulb temperature of 76°F, the same ventilation heat removal (latent and sensible heat) could be obtained at sea level as could be obtained at altitude with a ventilating gas whose characteristics were exactly the same except for a dry-bulb temperature of 50°F. Because a gas flow of 17.1 cfm was used in both the altitude and sea level runs, the mass flow of gas in the latter was considerably greater because of the gas density reduction at reduced barometric pressure. This high mass flow at sea level would have permitted a much larger sensible heat removal than at altitude if the temperatures were the same; it was to compensate for this large sensible heat capacity that the dry-bulb temperature of the sea level gas was raised and the temperature of the altitude gas was maintained relatively lower. This maneuver proved successful, and approximately the same amounts of sensible heat were removed from the suit at both pressure conditions. The latent heat removal depends largely on the water vapor pressure in the ventilating gas stream as opposed to the mass of oxygen in the stream, so the dew-point temperature was not changed from sea level to altitude.

While the final ventilation heat removal rate was very nearly the same from sea level to reduced pressure, the apparent cooling efficiency of the gas stream (the ratio of the end-of-run net heat removal rate to the corresponding mean metabolic rate) was reduced with reduced pressure. This change in efficiency was caused by the increase in metabolic rate with altitude at the higher work rate as a result of heat storage. This observation will be discussed in greater detail in subsequent paragraphs. These effects may have been influenced, in addition, by subject variation or other uncontrolled artifacts of the procedure. One obvious artifact was the experimental sequence, in that in every case the sea level modes preceded the altitude modes during the testing. It is apparent from an examination of the rectal temperature graphs and the means that progressive heat storage occurred during the experimental day. It was noted above that the average rectal temperature differential from the start to the end of each mode was 2°F; it should also be noted that an average rectal temperature differential of 4°F was observed between the beginning and the completion of the test day. This progressive increase in body temperature would be expected to produce an increased metabolic rate because of the so-called "Q_{10} effect," by which the metabolic rate is increased 13 percent for every 1°C increase in body temperature. Thus, by the end of the day (the altitude, 2.0 mph mode), the metabolic rate would be expected to be higher than at the corresponding sea level mode, because of the stored heat and the concomitant temperature rise.

In order to examine these effects, experiments could be accomplished in which the altitude and sea level conditions are varied randomly. Unfortunately, there are large practical drawbacks to this, including the lengthy instrumentation calibrations for pressure changes, the increased probability of altitude sickness in the subject and observer, etc. In order to examine what metabolic rates "would have been" without increasing body temperature from that observed during the preflight medical examination, appropriate lines were computed and are shown on the metabolic rate graphs for each subject. The lines, of course, are highly arbitrary, but nevertheless are useful in standardizing the data. When ventilation efficiencies are computed using these numbers, the seeming effects of altitude are no longer apparent.

One major difficulty in simulating altitude data from sea level data is demonstrated by the increased body heat storage rates observed at altitude. The results indicate that the ventilation heat removal reached its equilibrium maximum at altitude in an appreciably longer time than at sea level. Thus, while the "end-of-runs" data are similar, the total quantity of heat removed at altitude was lower than that removed at sea level; in other words, the curves of ventilation heat removal plotted against time became asymptotic to the final heat removal level more slowly at altitude than at sea level. This extended equilibrium time at altitude was probably a result of the comparatively lower mass flow of ventilating gas. Because the integral of the altitude heat removal curve is smaller than that of the sea-level heat removal curve, more heat was removed in the latter case than in the former, and thus more heat was stored during the altitude modes. The results of this heat storage on the other parameters, particularly metabolic rate, have already been discussed. It may prove possible to correct for this discrepancy by reducing the volume flow during sea level tests, although this would introduce other artifacts to the sea-level simulation technique. It will probably be sufficient instead to use computational extraction of altitude heat storage rates and Q_{10} - increased metabolic rates.

The body temperature results and the discussion earlier in this section have shown that high rates and quantities of heat storage were encountered in this experimentation. Several of the subjects, in fact, stored quantities of heat as great as 1000 Btu (note particularly the overall increase in rectal temperature during the test day). The maximum heat storage which is generally considered permissible from the standpoint of health and safety is 600 Btu; this figure is commonly used as design specification maximum, etc. It would appear from the test results that this figure is quite conservative when considerable muscular activity is occurring. As was described earlier, active skeletal muscle tissue rises notably in temperature during its activity, thereby storing a large quantity of the total metabolic heat in an apparently innocuous fashion. The subjects used in this experiment were in good health, and almost all of these who completed the test sequence stored at least 600 Btu, and a few of them as much as 1000 Btu, with no apparent physical ill-effects. The subjects who were unable to complete the tests were either those in relatively poor physical "shape" or those forced to abort the test as the result of suit sizing difficulties. None of the subjects showed the symptoms associated with excessive heat storage, although some of them expressed relevant complaints during the testing itself. On the basis of these observations, it is felt that 1000 Btu is a more meaningful heat storage maximum for exercising subjects than 600 Btu.

Another major difficulty in simulating altitude tests by sea level experimentation is shown by the minute volume results. In this experimentation, and in other experimentation in our and other laboratories, a definite and statistically significant decrease in minute volume has been observed to occur with decreased barometric pressure. A statistical investigation by the authors has shown that no significant decrease in respiratory rate occurs; the significant factor therefore would seem to be tidal volume. When minute volume is adjusted for metabolic rate so that the effects of work are normalized, the sea level-to-altitude difference becomes even more apparent (see Table II). Various hypotheses have been proposed to account for this phenomenon, but none of them has proved completely satisfactory. This effect causes a reduction in respiratory water loss with reduced pressure, and hence a reduction in the latent heat loss of respiration. Because this is one of the primary effects of minute volume of concern in suit testing, it may be possible to simulate altitude conditions at sea level by using a correspondingly higher dew-point temperature of the inspired gas in the sea level modes. However, this possibility was not examined in this experimentation.

A further discrepancy between the altitude and sea level modes was noted with respect to skin temperature. It was observed that the skin temperatures of the subjects were generally lower at the altitude modes than at the sea level modes. One would expect that this was a result of increased sweating at altitude, but the latent heat removals were the same, or even very slightly lower, at altitude than at sea level. It would appear that the lowered skin temperatures were a consequence of the reduced temperature of the ventilation gas which was used at altitude and/or a shift to a mass transfer mechanism for heat removal. The skin temperature effect is contrary to that observed by Wortz, et al. (Reference 8) for men in light clothing. The differences can probably be explained by the different heat transfer situations existing between the shirtsleeve and pressure suit environments as interpreted by Burris, et al. (Reference 14). In the case of the ventilated pressure suits, evaporation of moisture from the skin serves as the primary method of cooling. The mass transfer correlations predict an increase in mass transfer coefficient at reduced pressure, as a consequence of the increased diffusivity of water vapor in the ventilating gas. Therefore, for the same energy dissipation rate, a smaller driving potential is required for mass transfer. The driving potential in this case is represented by the difference in water vapor partial pressure between the skin and the atmosphere (less the vapor pressure lowering due to dissolved electrolytes in sweat). The water vapor partial pressure at the skin can be assumed to be that for saturation at the skin temperature. Consequently, lower driving potential at reduced pressure would appear to lead to lower skin temperatures. The increased skin temperature obtained at higher work rates in ventilated pressure suits would appear to be a result of the requirement for increased mass transfer at a constant ventilating flow. The opposite skin temperature effect obtained with subjects at reduced pressure in shirtsleeve environments is possibly due to the greater sensible heat loss from the body (by radiation and convection) which is controlled by skin temperature.

If this explanation is correct, then sea-level simulated altitude testing will be forced to sacrifice adequate skin temperature response for sensible heat removal. Further testing should be carried out to examine this problem more thoroughly, because it could be of major importance in extrapolating sea level to altitude results.

In examining the graphs of the results, certain parameters tend to be abnormal or extreme for the first data points for several of the subjects. It is felt that these data points reflect the physiological results of the initial psychological stress brought about by anxiety and the other stresses of the test situation. Also, most of the subjects required several minutes at the start of each mode, particularly the initial modes, during which they attempted to adapt their walking to the restrictions of the pressurized suit, the attached gear and piping, and the treadmill. Because of these factors, the physiological parameters for individual subjects and modes occasionally appear anomalous for the initial data points. In addition, amid the data are isolated data points for which the results are obviously erroneous. These data, included for consistency, may be the results of human error, particularly when they constitute a major deviation from an otherwise fairly regular line. Minor variations may be expected from the predictable sources of error analyzed in Section 5, as well as from minor variations in the parameter being measured.

The experimentation described in this report represents a considerable improvement in several respects over related experimentation donepreviously in our laboratory and other laboratories. One major problem area in the past has been the technique used to measure metabolic rates; methods which depend upon the measurement of only one of the index gases--carbon dioxide or oxygen--are limited by a large theoretical error because the respiratory quotient must be assumed. In this work, measurements were made of both of these gases, limiting the error to that of the instruments. Previous experimentation has been adversely affected by use of small numbers of subjects. The results published here, as well as the results of other tests, demonstrate that the range of physiological data for pressure-suited subjects is much greater than that occurring with unsuited subjects. For this reason alone, a sufficient number of subjects is necessary. In addition, the larger the number of subjects, the more confidence is permissible with the results.

In general, the results of this experiment may best be compared with those of Albright, et al. and Wortz, et al. (Reference 3). The results of Albright, et al., indicated that a "heat balance" was achieved with a heat storage rate of 0 Btu/hr in one of the tests and 167 Btu/hr in the other; it is interesting to speculate about how this computed balance can be rationalized in light of the data presented, which indicated a heat storage rate of approximately 400 Btu/hr in one case. The justification apparently involved the largely unmeasured rectal temperature and the assumed metabolic rates. Albright, et al., however, employed a different type of pressure suit from that used in the present study, and observed ventilatory heat removal rates (1440 Btu/hr) which were similar to those observed in this test. The work of Wortz, et al. (1964) employed the same type of suit as that employed in this study. The results reported in this document corroborated both the metabolic rates and the ventilation heat removal rates observed in the previous study with the same suit type.

SECTION 8

CONCLUSIONS

The following conclusions have been made on the basis of the results of this experiment:

a. The overall mean metabolic rates of subjects wearing the Gemini G2-C pressurized suit were 2070 Btu/hr at a treadmill walking speed of 1.4 mph and 2525 Btu/hr at a treadmill walking speed of 2.0 mph, with associated mean net ventilatory heat removal rates of 1259 Btu/hr and 1375 Btu/hr, respectively.

b. The pressure suit ventilation gas inlet conditions employed in this experiment (dew-point temperature of 33°F, flow rate of 17.1 ft^3/min., suit pressurized to 3.7 psig over cabin ambient, and drybulb temperatures of 76°F at sea level and 50°F at altitude) resulted in equivalent rates of ventilation heat removal for both the sea level and altitude conditions.

c. Pressure suit tests at sea level were not fully representative of altitude conditions, largely because the rate of ventilation heat removal became asymptotic to the final level of heat removal more rapidly at the higher pressure.

d. Heat storage considerably higher than the accepted maximum of 600 Btu can safely be permitted under conditions of high muscle activity. It would appear that, when the skeletal muscle masses are active and thus producing and storing large quantities of heat, total heat storage of as much as 1000 Btu can occur.

e. Heat storage, under the conditions of this experiment, apparently results in a noticeable "Q_{10} effect" during periods of exercise approaching 1 hr in duration.

f. Apparently as a consequence of conclusions c and e above, higher metabolic rates were obtained for the high exercise rate at altitude than at sea level.

REFERENCES

1. Nelson, W.G.: Final Report, Pressure Suit Test Program, Project Apollo. Rep. SS-1018, AiResearch Mfg. Co., Sep. 26, 1962.

2. Lang, R.: Experimental Evaluation of Ventilation Effectiveness of International Latex MK-2 Full Pressure Suit for Apollo Space Suit Program. Rep. SVHSER-2599, Hamilton Standard Div. of United Aircraft, April 15, 1963.

3. Wortz, E.C.; Harrington, T.J.; Edwards, D.K.; and Diaz, R.A.: Heat Balance Study. Rep. SS-952 (NASA Contract 6-16139), AiResearch Mfg. Co., June 25, 1963.

4. Albright, G.A.; Kirby, M.; Benjamin, F.B.; Beck, A.; and Frankel, G.G.: Ventilation Effectiveness of the Apollo Prototype Space Suit. Paper presented at 35th Annual Meeting, Aerospace Medical Association (Miami Beach, Fla.), May 1964.

5. Harrington, T.J.; Edwards, D.K.; and Wortz, E.C.: Metabolic Rates in Pressurized Pressure Suits. Paper presented at 35th Annual Meeting, Aerospace Medical Association (Miami Beach, Fla.), May 1964.

6. Wortz, E.C.; Belton, J.; Browne, L.E.; Diaz, R.A.; Edwards, D.K.; Prescott, E.J.; Nelson, W.G.; and Krumland, L.: Gemini Extravehicular Suit Pressurization Ventilation Test Series. Rep. SS-3135 (Rev. 1), AiResearch Mfg. Co., June 19, 1964.

7. Lusk, G.: Analysis of Oxidation of Mixtures of Carbohydrates and Fat (24th paper on animal calorimetry) J. Biol. Chem., vol 59, 1924, p. 41.

8. Wortz, E.C.; Diaz, R.A.; Green, F.H.; Sanborn, W.G.; Edwards, D.K.; Prescott, E.J.; and Scherer, G.R.: Reduced Barometric Pressure and Respiratory Water Loss. Rep. LS-136 (Contract AF 41(609)-2389), AiResearch Mfg. Co., Oct. 31, 1964.

9. Meehan, J.P.: Body Heat Production and Surface Temperature in Response to a Cold Stimulus. J. Appl. Physiol., vol. 7, 1955, p. 537.

10. Dubois, E.F.; Ebaugh, F.G.; and Hardy, J.O.: Basal Heat Production and Elimination of Thirteen Normal Women at Temperatures from 22°C to 35°C. J. Nutrition, vol. 48, 1952, p. 257.

11. Dubois, E.F.: The Many Different Temperatures of the Human Body and Its Parts. West J. of Obstet. and Gyn., vol. 59, 1951, p. 476.

REFERENCES (Continued)

12. Aikas, E.; Kauonen, M. J.; Phronen, P.; and Ruosteenosa, R.: Intramuscular, Rectal and Oesophageal Temperature During Exercise. Acta Physiol. Scand., vol. 54, 1962, p. 366.

13. Hill, A. U.: Energetics of Relaxation in Muscle Tissue. Proceedings of the Royal Society of London, ~~S. B.~~, vol. 136, 1949, p. 211.
Section B

14. Burriss, W.; Lin, S. H.; and Berenson, P.: Study of Thermal Processes for Man in Space. Rep. SS-3280 (Contract NASW-1015), AiResearch Mfg. Co., Feb. 8, 1965.

EXPERIMENT NO. 1 (columns 1–5) | DATE Mo. Day Yr. (columns 72–77) | SUBJECT Initials (columns 78–80) | BAROMETER ____ IN. HG

TIME		DEW POINT		DRY BULB		PRESSURE		SIGNIFICANT DATA 1 = yes 0 = no	
		OUT	IN	OUT	IN	OUT	IN		
HR	MIN	°F	°F	°F	°F	IN. HG	IN. HG	↓	
6-7	9-10	11 20	21 30	31 40	41 50	51 60	61 70	71	
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		

PD-7

EXPERIMENT NO. 2 (1–5) DATE Mo. Day Yr. SUBJECT Initials (78–80)

TIME		pO_2 OUT	pO_2 IN	WATER OUT	METER TEMP	T-MILL SPEED	CO_2 OUT		VOLUME METER
HR	MIN	MM HG	MM HG	GRAMS	°F	MPH	VOL%	X	LITERS
6-7	9-10	11 — 20	21 — 30	31 — 40	41 — 50	51 — 60	61 — 70	71	72 — 77
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		

PD- 11

EXPERIMENT NO. 3 (1–5)	DATE Mo. Day Yr.	SUBJECT Initials (78–80)	OXYGEN BOTTLE NO.

TIME HR	TIME MIN	PULSE BEATS/MIN	RECTAL TEMP °F	SKIN TEMPERATURE 1 °F	SKIN TEMPERATURE 2 °F	SKIN TEMPERATURE 3 °F	SKIN TEMPERATURE 4 °F	X	NON OXYGEN PPM
6-7	9-10	11 20	21 30	21 40	41 50	51 60	61 70	71	72 77
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		

PD-12

EXPERIMENT NO. 4 | DATE Mo. Day Yr. | SUBJECT Initials

1 5 | 78 80

TIME		SKIN TEMPERATURE					METER PRESSURE		
		5	6	7	8	9			
HR	MIN	°F	°F	°F	°F	°F	IN. HG	X	
6-7	9-10	11 20	21 30	31 40	41 50	51 60	61 70	71	72 77
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		

PD-13

EXPERIMENT NO. 5		DATE Mo. Day Yr.		SUBJECT Initials					
		1	5			78	80		
TIME		SUIT DEW POINT		SUIT DRY BULB		SUIT PRESSURE		MEAN TANK AIR TEMP	
		OUT	IN	OUT	IN	OUT	IN		
HR	MIN	°F	°F	°F	°F	IN. HG	IN. HG	X	°F
6-7	9-10	11 20	21 30	31 40	41 50	51 60	61 70	71	72 77
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		
		•	•	•	•	•	•		

PD-14

EXPERIMENT NO. 6 (columns 1–5) | DATE Mo. Day Yr. | SUBJECT Initials (columns 78–80)

TIME		SUIT FLOW METER TEMP		SUIT FLOW METER PRESS		SUIT FLOW METER RATE			MEAN TANK WALL TEMP
		OUT	IN	OUT	IN	OUT	IN		
HR	MIN	°F	°F	IN. HG.	IN. HG.	CFM	CFM	X	°F
6-7	9-10	11 – 20	21 – 30	31 – 40	41 – 50	51 – 60	61 – 70	71	72 – 77
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		
		.	.	.	.	.	.		

PD-15